Dual-Phase Liquid Argon Time Projection Chambers

- Liquid Argon TPCs
  - The dual-phase concept
  - A bit of history
- The dual-phase protoDUNE: $6x6x6\ m^3$ (WA105)
- The dual-phase pilot detector: $3x1x1\ m^3$

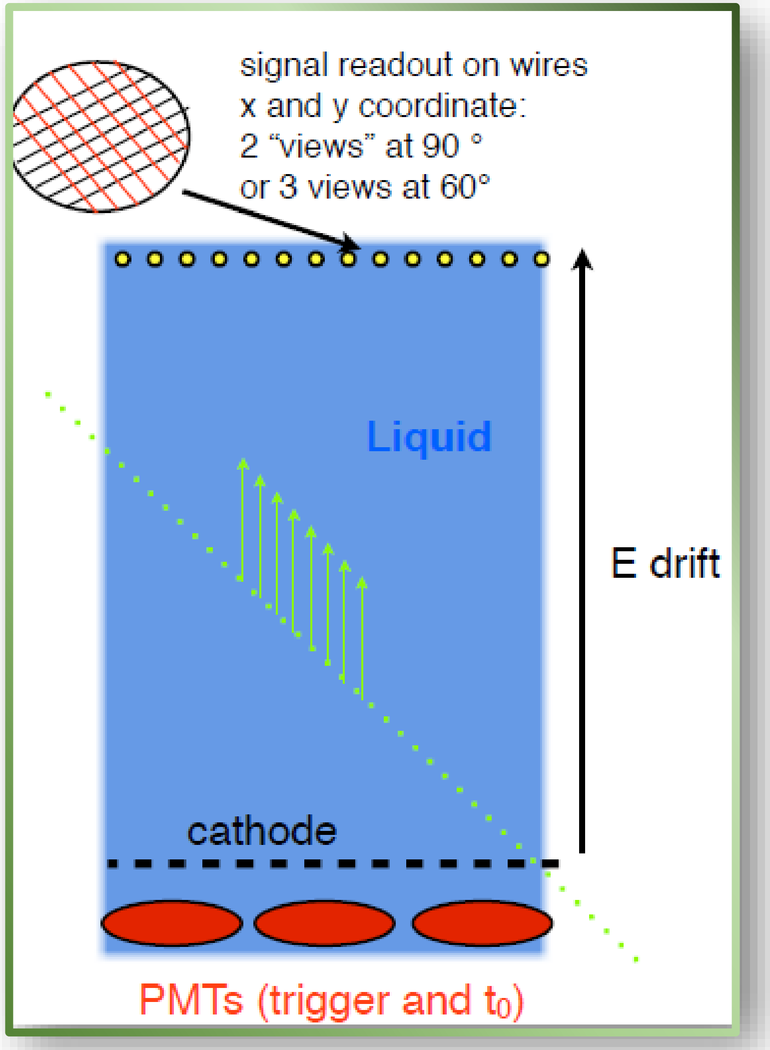
Liquid argon Time Projection Chamber (LAr TPC)

- **The liquid argon Time Projection Chamber (LAr TPC) detection technique**
  - liquid argon volume in an electric field with an electron collection system
  - Passing through particle will produce primary ionization along its track. The ionization electrons will travel through the field and be collected and measured by the collection system
  - Imaging is provided by wire planes or a micropattern structure placed at the end of the drift path, continuously sensing and recording the signals induced by the drifting electrons
- Future experiments will use LAr detectors of tens of kilotons: the **DUNE** experiment will address the next major questions in neutrino physics with a giant liquid Argon TPC of 10 kton

  Why?
  - LAr TPCs provide a complete 3D image of the interaction final state particles over a wide range of energies

    with efficient background rejection and good energy reconstruction
  - It's a noble element allowing ionization electrons drifting through it, and it is relatively cheap

→an **extensive R&D program** is on-going world-wide



Liquid argon Time Projection Chamber (LAr TPC)

BUT! Liquid **Ar must be kept extremely pure** for the electrons to drift across the TPC without attaching to impurities

→ in highly purified liquid argon ionization tracks could **be transported undistorted by a uniform electric field over distances of the order of meters**

AND **drift distances of the order of meters require voltages in the hundred of kV range**

→ Test a technique based on the **dual-phase LIQUID/VAPOUR Argon** charge readout for a signal over noise gain much larger than the one with standard techniques.

Dual-phase LAr TPC: fully homogeneous detector with one single vertical drift volume.

Key-feature: **Amplification of the signal by charge avalanche in the gas phase**

→Larger signal/noise ratio

→overall better image quality

Allows constructing detectors with longer drift distances

- **5 LAr TPCs currently considered within DUNE**:

❖ The 3x1x1 m3 dual-phase

❖ The protoDUNE single-phase

❖ The protoDUNE dual-phase

❖ The DUNE Far Detector single-phase (10kton)

❖ The DUNE Far Detector dual-phase (10kton)

Detector	Active LAr volume (m3)	Nb of drift regions	Drift length (m)	HV at cathode (kV)	
				250V/cm	500V/cm
3x1x1 Dual-phase	23	1	1	-25	-50
protoDUNE Single-phase	216	2	3.6	-90	-180
protoDUNE Dual-phase	216	1	6	-150	-300
DUNE 10kton Single-phase	8640	4	3.6	-90	-180
DUNE 10kton Dual-phase	8640	1	12	-300	-600

THE DUAL-PHASE CONCEPT

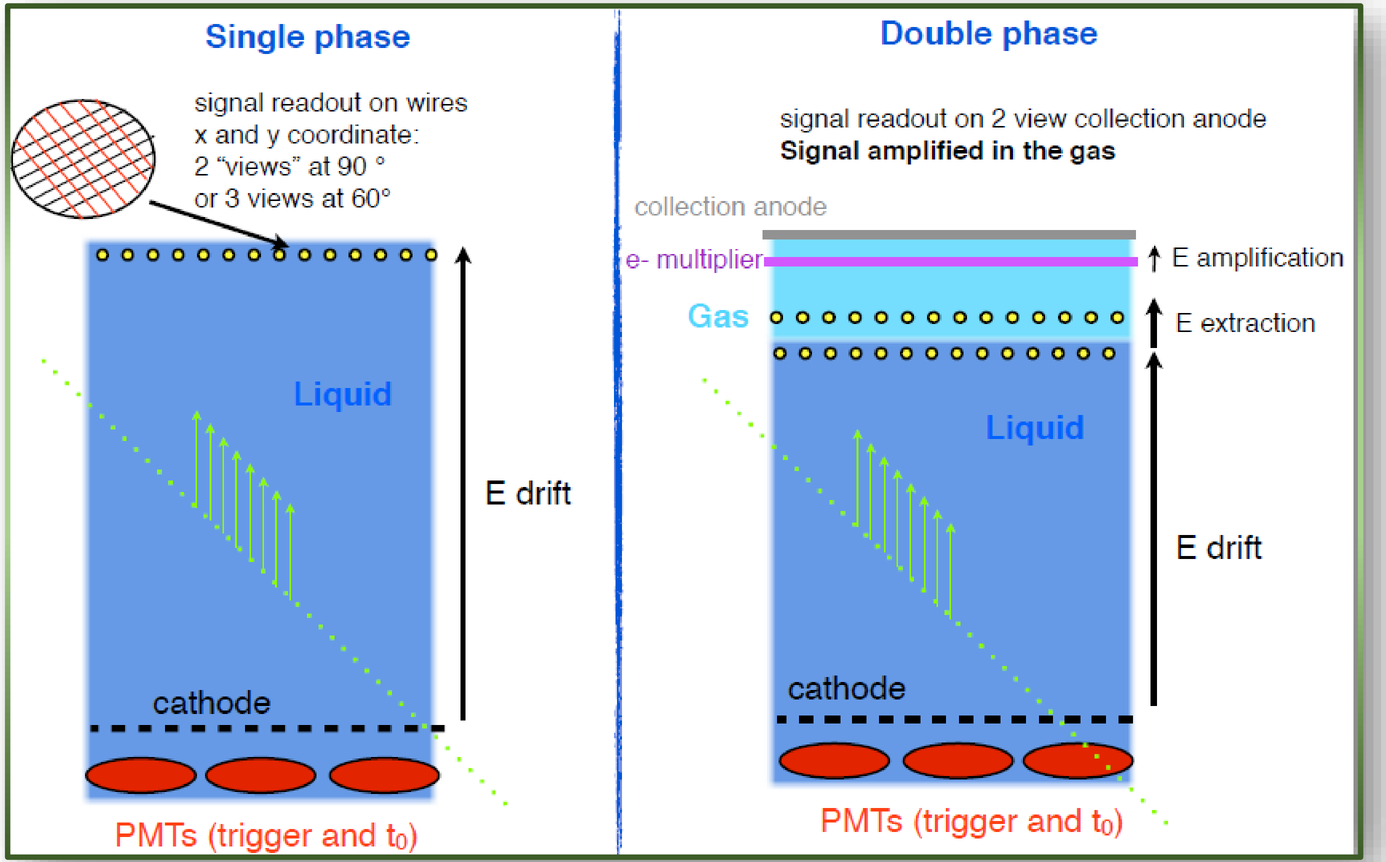
LAr TPC: Basic technique established → Technical Challenges towards very long drifts and very massive detectors

- **Long drifts requires ultra high purity → charge attenuation along the drift path**
- **No charge amplification in single phase**

→ Compensate the effect with charge multiplication at the anode

Traditional liquid argon TPC readout scheme

- e- drift in the liquid phase in a uniform electric field
- read out by a system of wires: one collection view and one or more induction views.
- No amplification of the initial ionization signal: collection at the anode after losses due to the presence of impurities along the drift path.



The dual-phase scheme

vertical drift up a region with a stronger electric field

→ ***extraction of the electrons to the gas phase above the liquid level.***

→ ***avalanche multiplication of the electrons in the pure argon gas in confined regions with very strong electric fields***

(Micro-pattern detectors like the Large Electron Multipliers **(LEM)**, located just above the liquid level)

THE DUAL-PHASE CONCEPT

Lar TPC: Basic technique established → Technical Challenges towards very long drifts and very massive detectors

- **Long drifts requires ultra high purity → charge attenuation along the drift path**
- **No charge amplification in single phase**

→ Compensate the effect with charge multiplication at the anode

Charge Collection on anode readout (2 orthogonal views) **(no induction plane)**

↑

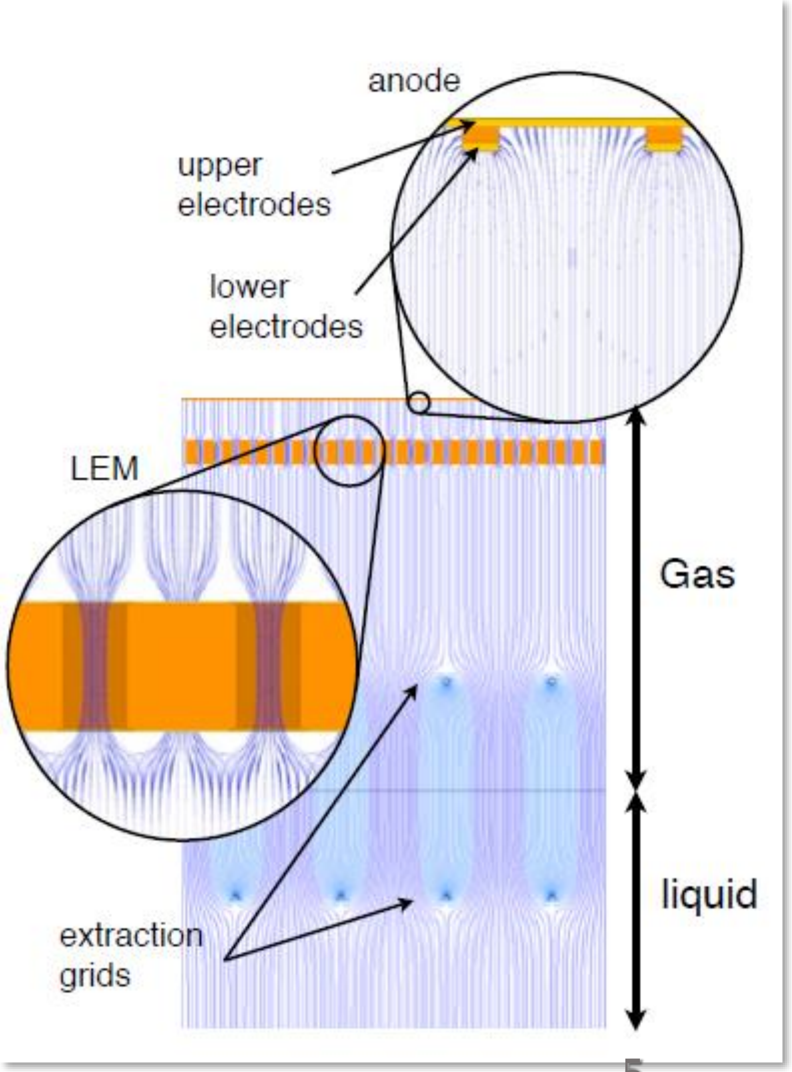
Charge multiplication: LEM – Large Electron Multipliers

↑

Electrons extraction from liquid to gas phase through a grid

↑

Ionization electrons drift towards the liquid argon surface



Towards the 10kton dual-phase TPC

- **2003**: **The Concept**
  A. Rubbia, "Experiments for CP-violation: A giant liquid argon scintillation, Cherenkov and charge imaging experiment?" hep-ph/0402110

large cryogenic tanker of the needed size. Is a strong R&D program required to extrapolate the liquid Argon TPC to the 100 kton scale? Or can it be achieved in say one (or two) step(s)? In the following, we try to address the feasibility of a single volume 100 kton liquid argon detector.

The basic design parameters can be summarized as follows:

3. Charge amplification to allow for extremely long drifts: the detector is running in bi-phase mode. In order to allow for long drift (≈ 20 m), we consider charge attenuation along drift and compensate this effect with charge amplification near anodes located in gas phase.

- **2008-2011**: **Proof of principle with 10x10cm^2 double-phase 3L LAr LEM-TPC prototype**
  A. Badertscher *et al*, "Operation of a Double Phase pure argon Large Electron Multiplier Time Projection Chamber: comparison single and double phase" NIM A617 (2010) p188-192
  A. Badertscher *et al*, "First operation of a double phase LAr Large Electron Multiplier Time Projection Chamber with a two- dimensional projective readout anode" NIM A641 (2011) p48-57

In double phase operation the liquid argon surface is positioned between the two extraction grids in a 2.8 kV/cm electric field. Electron amplification occurs in cold argon vapour (~1 bar and 87 K), about 3.4 times denser than at STP.

The figure 5 shows a typical cosmic ray long track. In this case no noise reduction was applied, because the amplification improves considerably the signal to noise ratio (S/N = 800/10).

Towards the 10 kton dual-phase TPC

- **2008-2011: Proof of principle with 10x10cm^2 double-phase 3L LAr LEM-TPC prototype**

A. Badertscher *et al*, NIM A617 (2010) p188-192
A. Badertscher *et al*, NIM A641 (2011) p48-57

LEM inserted in liquid

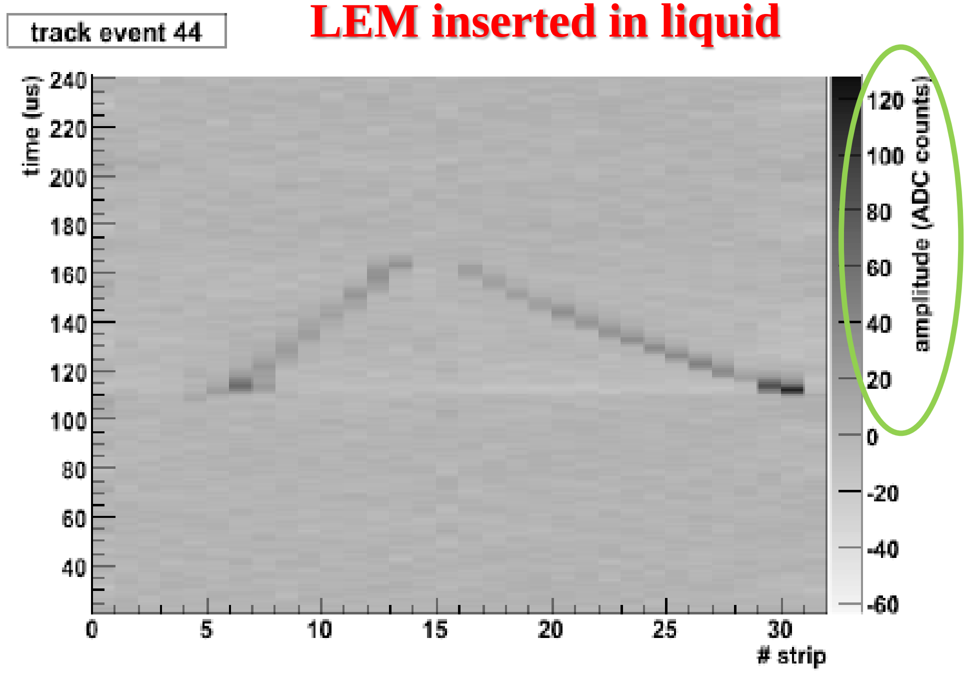


Figure 4: Typical cosmic muon track with LEMs immersed in liquid (gain 1).

LEM in dual-phase

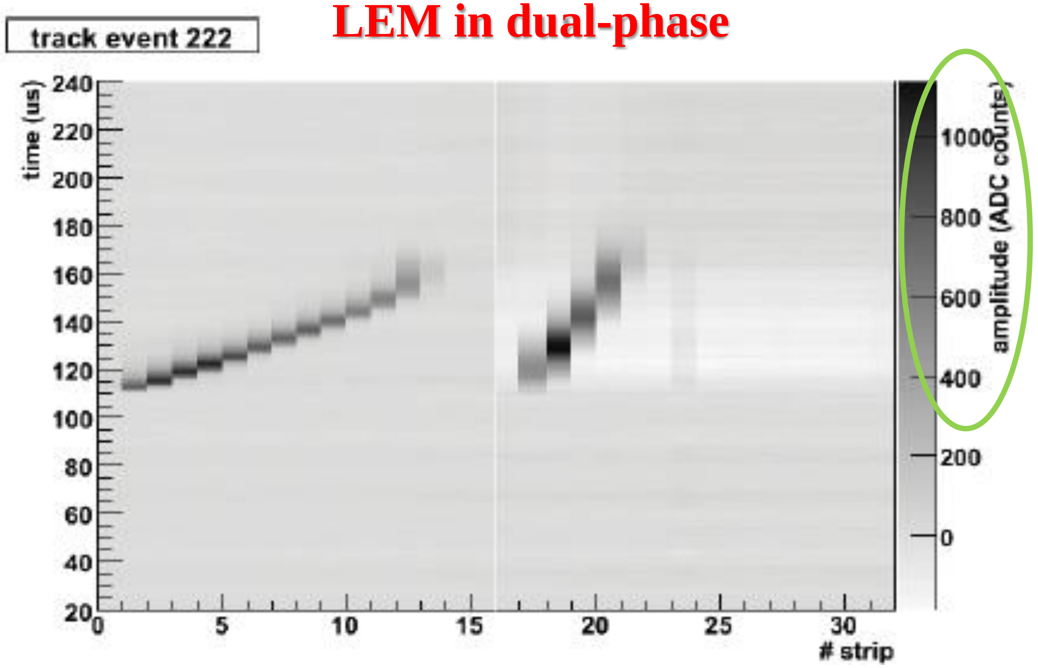


Figure 5: Typical cosmic muon track in double phase operation.

From the average energy loss of cosmic muons we evaluate the effective gain of the LEM-TPC to be about 10: a minimum collected charge on the anode is 100 fC/cm. It is evident the improvement of the signal to noise ratio between the liquid operation and the double phase operation. In addition a stable gain of 10 can compensate the degradation of the signal due to impurities for very long drift paths. This fact makes the LEM-TPC an interesting device for very long drift, cost-effective, liquid argon experiments for neutrino physics and proton decay search.

Towards the 10 kton dual-phase TPC

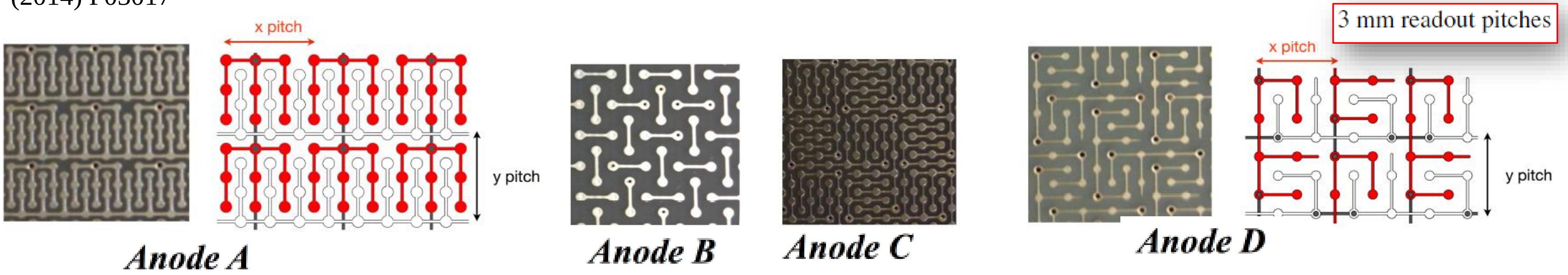
- **2011**: **First successful operation of a 40x80cm^2 ton-scale device**

"First operation and drift field performance of a large area double-phase LAr Electron Multiplier Time Projection Chamber with an immersed Greinacher high-voltage multiplier" JINST 7 (2012) P08026
"First operation and performance of a 200 lt double phase LAr LEM-TPC with a 40x76 cm^2 readout" JINST 8 (2013) P04012

> We have produced and successfully operated the largest LAr LEM-TPC with 2D readout anode of an area of 40×76 cm^2 (~ 0.5 m^2) and 60 cm drift. During a very successful run with double phase ultra-pure argon at 87 K, the detector was exposed to cosmic rays and recorded a large number of events during a long-term data-taking period. A stable effective gain 14 was reached, giving an excellent signal to noise ratio of > 30 for a MIP. The detector performance has been studied and a

- **2012-2013**: **R&D towards final, simplified charge readout and Approval of WA105 6x6x6 m^3 proposal by CERN at CERN Neutrino Platform**

"Long-term operation of a double-phase LAr LEM Time Projection Chamber with a simplified anode and extraction-grid design" JINST 9 (2014) P03017



2D anode prototypes showing the copper track pattern that allows a 2 view readout on the same circuit board.

Towards the 10kton dual-phase TPC

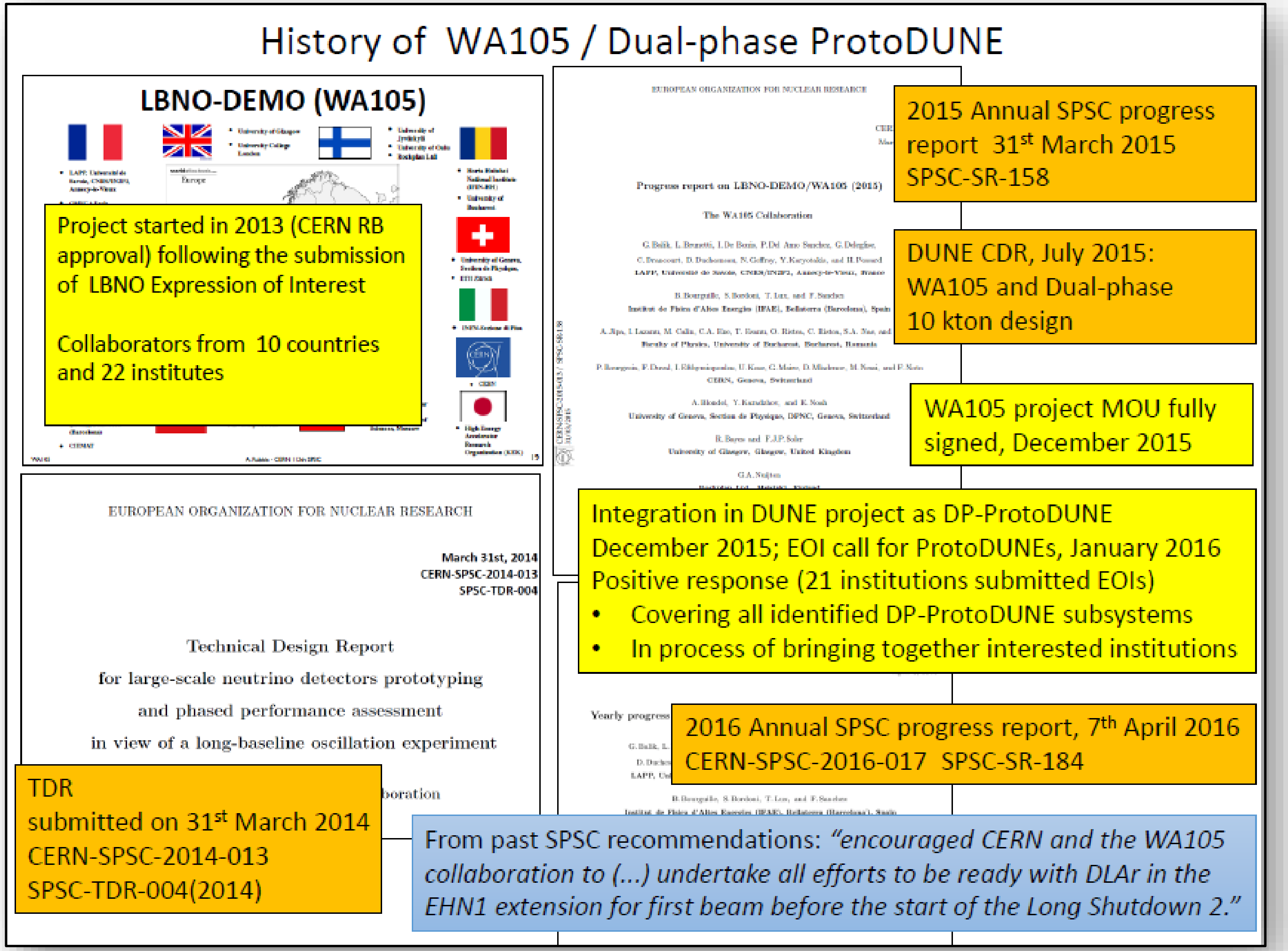
- **2014: Optimisation of anode & LEM geometries and submission of WA105 6x6x6 m^3 TDR**

"Performance study of the effective gain of the double phase liquid Argon LEM Time Projection Chamber" JINST 10 (2015) 03, P03017
"Large-scale neutrino detector demonstrator for phased performance assessment in view of a long-baseline oscillation experiment" L. Agostino *et al*. CERN-SPSC-2014-013, SPSC-TDR-004

- **2015: Design and development of 3x1x1 m^3 and 6x6x6 m^3 detectors**

Progress Report on LBNO-DEMO/WA105 (2015) CERN-SPSC-2015-013, SPSC-SR-158
Short Status Update on LBNO-DEMO/WA105 (2015) CERN-SPSC-2015-027, SPSC-SR-166

& WA105 becomes part of DUNE prototyping effort known as protoDUNE-DP



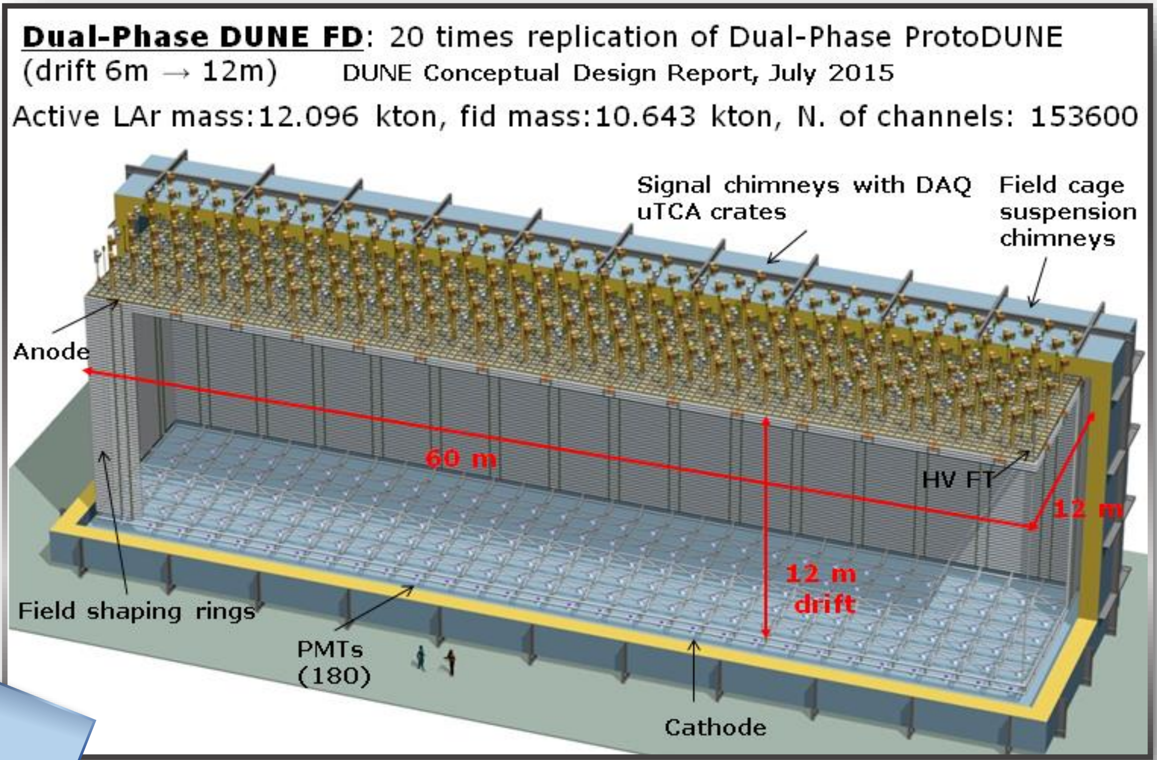
•2017→ … First operation of 3x1x1 m^3 (O(10-ton) scale) detector

→ 2018 (→?) First operation of 6x6x6 m^3 (300-ton scale) detector

Towards the 10kton dual-phase TPC

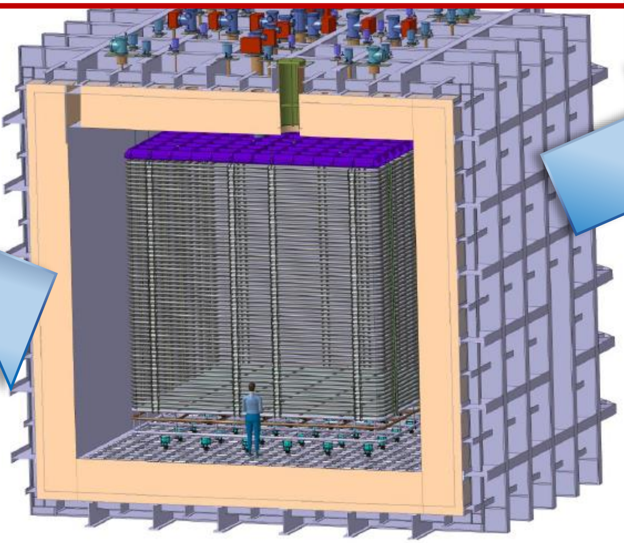
Advantages of double-phase design:
- Anode with 2 collection (X, Y) views (no induction views), no ambiguities
- Strips pitch 3.125 mm, 3 m length
- Tunable gain in gas phase (20-100), high S/N ratio for m.i.p. > 100
- Reduced number of readout channels
- No materials in the active volume
- Accessible and replaceable cryogenic FE electronics, high bandwidth low cost external μTCA digital electronics

Much longer drift → construction of very large size detectors and reduction of number of readout channels. The process of gas amplification in pure argon is the object of intensive R&D: **STAGED APPROACH**



- **80 CRP units**
- **60 field shaping rings**
- **240 signal FT chimneys**
- **240 suspension chimneys**
- **180 PMTs**
- **153600 readout channels**

LArProto 3x1x1m^3 25ton DP LAr TPC at CERN
Cryo installation, feedthroughs, tank, detector integearation



WA105/ProtoDUNE DP 6x6x6m^3 300ton DP LAr TPC LAr TPC at CERN
Large surface charge readout, long drift, high voltage for drift field, physics/performance with test beam

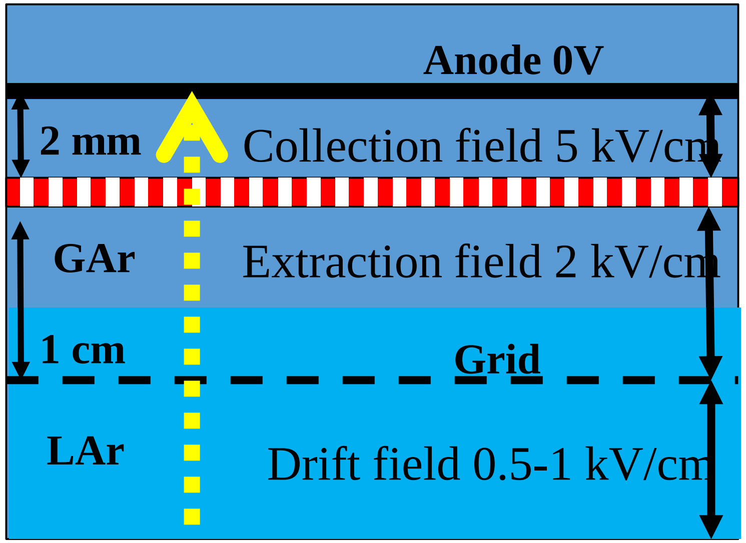
DUNE DP 60x12x12m^3 10kton DP LAr TPC Underground at Sanford
LBL neutrino physics (CP violation, MH hierarchy), SN, nucleon decay, neutrino astrophysics

Towards the 10kton dual-phase TPC

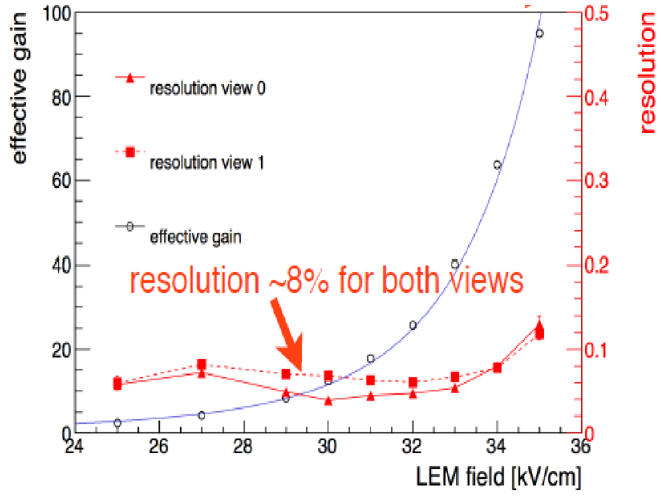
- **LEM: Field of 25- 35kV/cm.**
- **Typical gain obtainable tunable (~20 minimum)** → largely improves the signal/noise ratio
- Operation of these detectors in the **gas phase is a delicate aspect**: preservation of the purity of the argon implies avoiding the use of a gas mixture with components dealing with the quenching of UV photons, produced by the de-excitation the argon atoms during the avalanches.
- **Printed circuit anode with a 2D structure providing two collection views. No need for the induction plane.**

  The pattern was optimized to ensure 50:50 charge sharing between both views and best resolution on energy loss/unit length

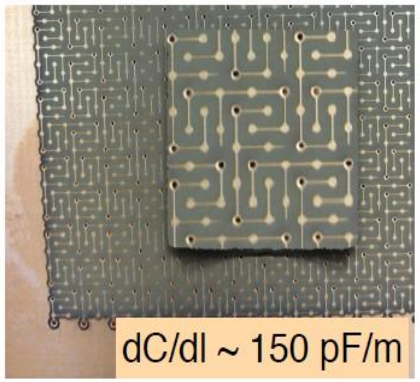
THE DUAL-PHASE protoDUNE (6x6x6 m^3)

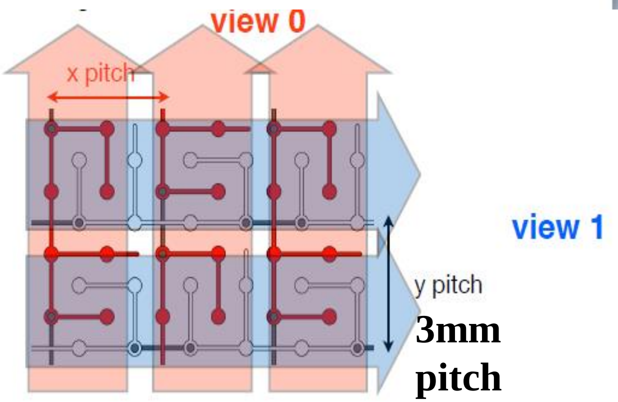


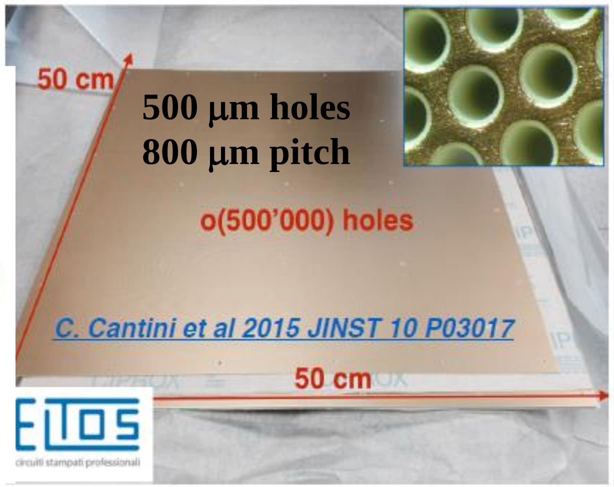
LEM (1mm)
25-35 kV/cm



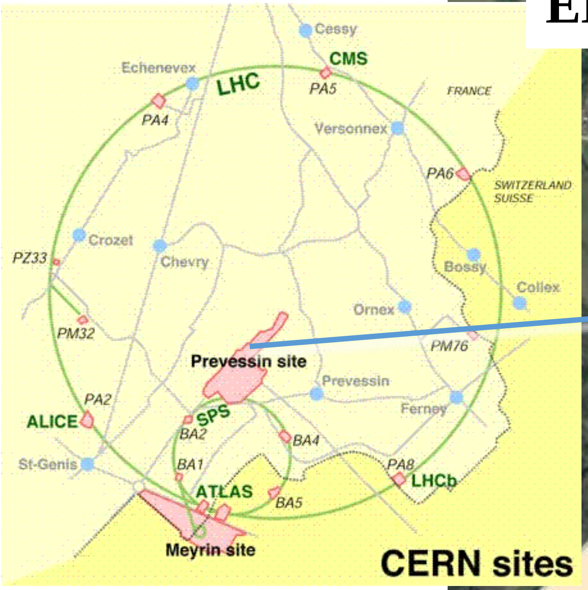
50x50 cm² LEM

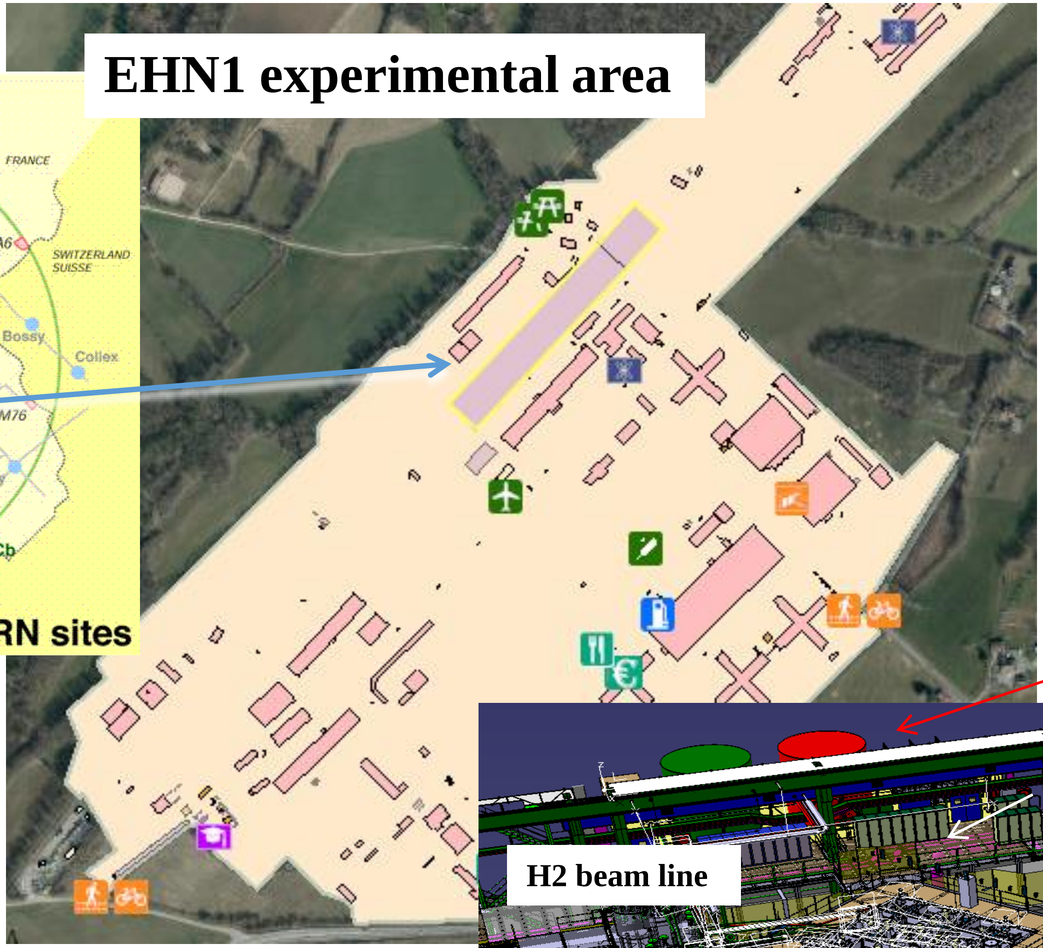


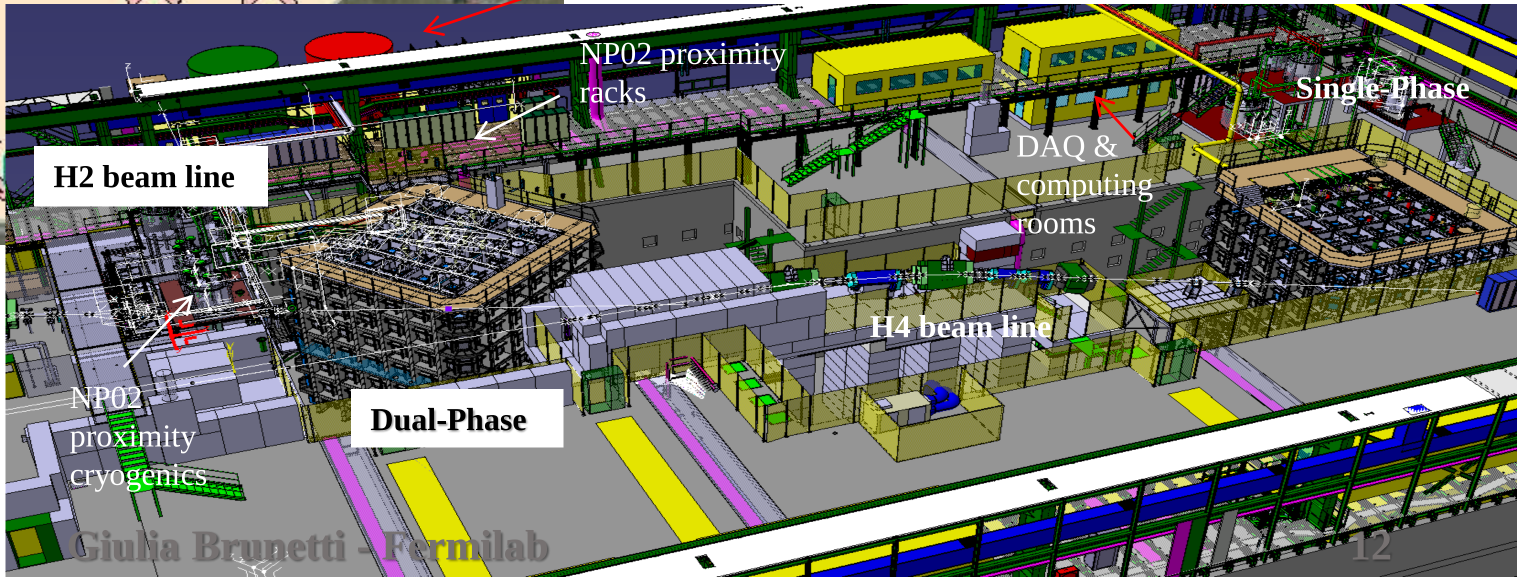




THE DUAL-PHASE protoDUNE (the CERN Neutrino Platform)





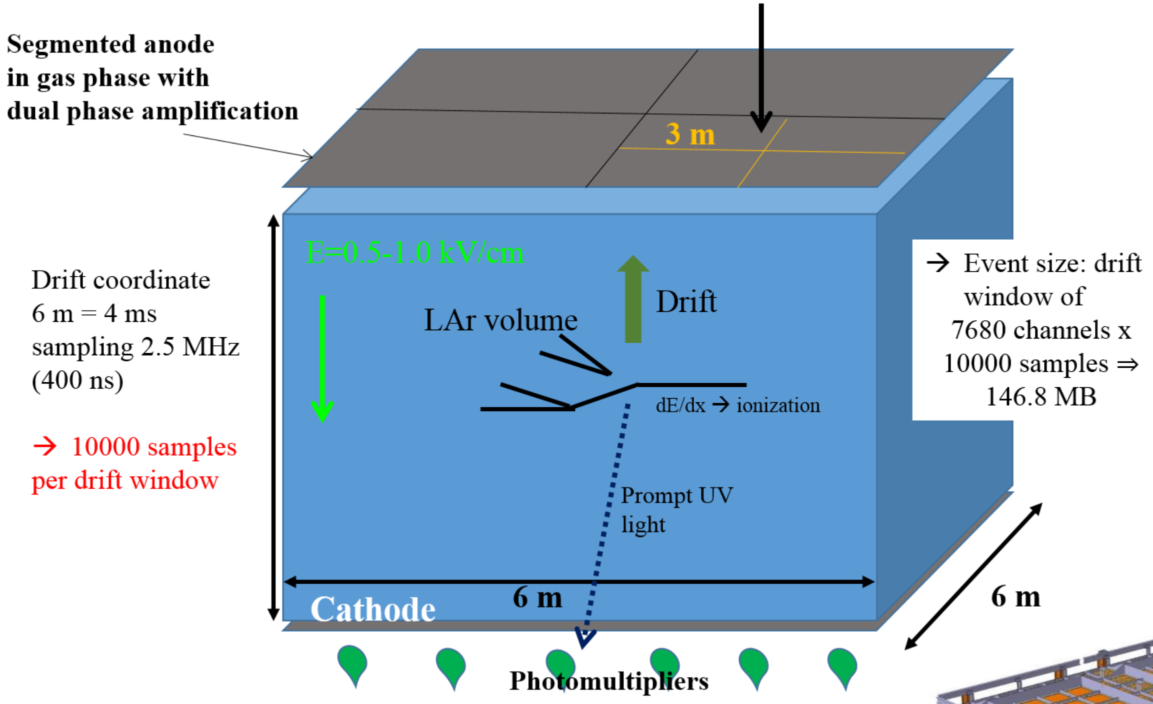


See: **Plans for ProtoDUNE dual-phase**
Dario Autiero, DUNE Collaboration Meeting, January 2017

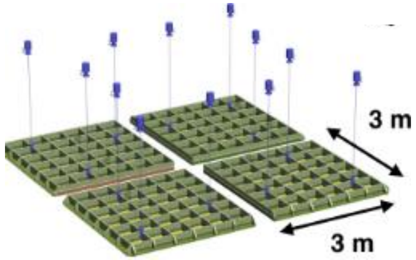
THE DUAL-PHASE protoDUNE

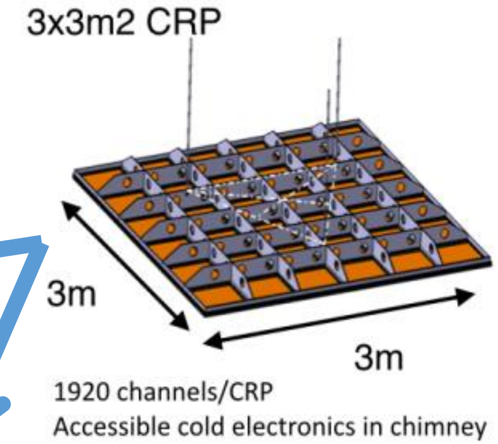
Dual phase liquid argon TPC
6x6x6 m³ active volume

X and Y charge collection strips
3.125 mm pitch, 3 m long →7680 readout channels

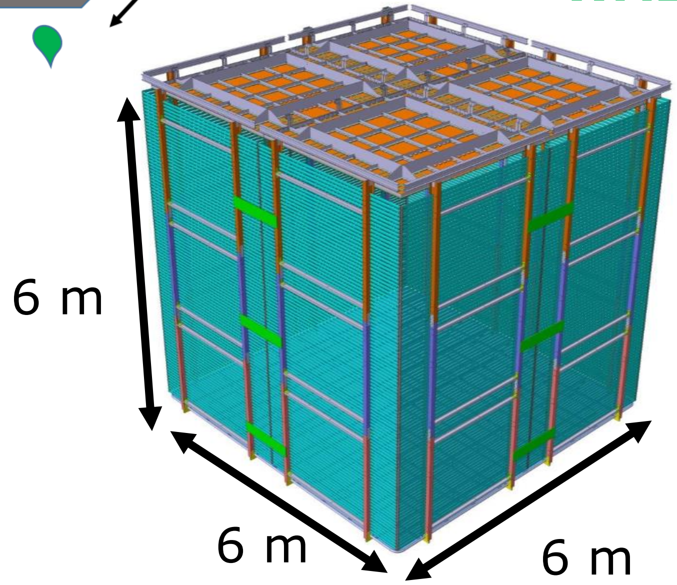


The Dual-Phase ProtoDUNE/WA105 6x6x6 m³ detector is built out of the same **3x3m² Charge Readout Plane units (CRP)** foreseen for the 10 kton Dual-Phase DUNE Far Detector

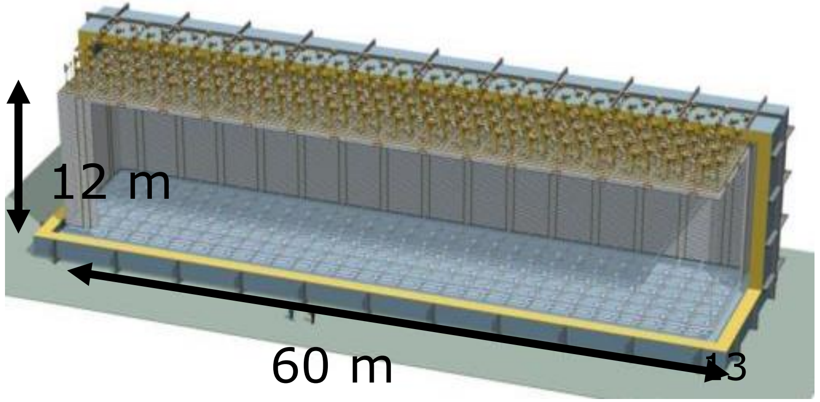




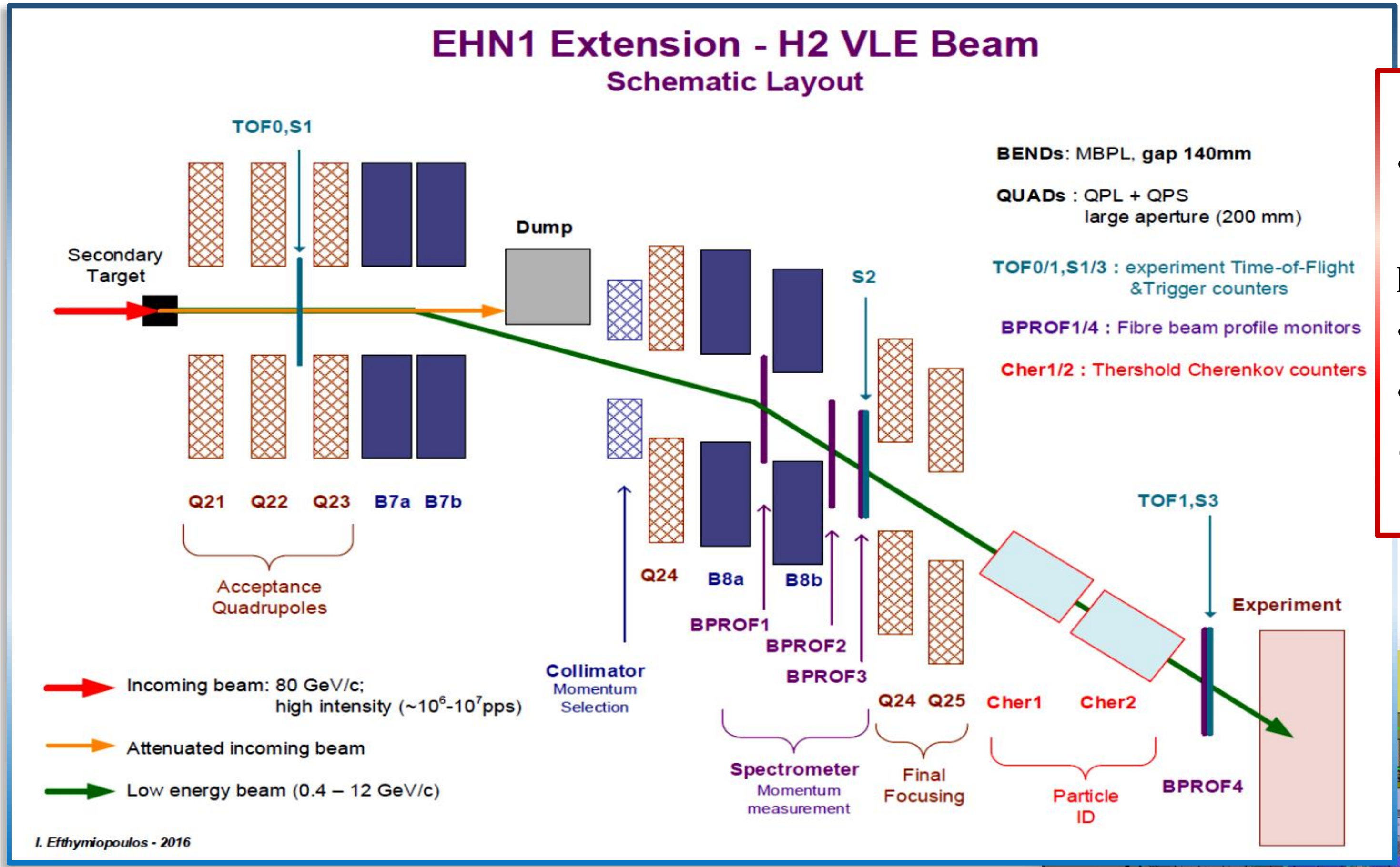
WA105: 4 CRP



10 kton: 80 CRP



THE DUAL-PHASE protoDUNE – The H2-VLE Beamline



Tertiary beam on H2 beamline:

- **Mixed hadrons beam 1-12 GeV/c** (momentum bite 5% , can be reduced to 1% with integrated spectrometer measurements)

pions, kaons, protons + electrons contamination at low energies

- Pure electron beams
- Parasitic muon halo

→O(100) M beam triggers to be acquired in 2018 in 120 days of beam operation

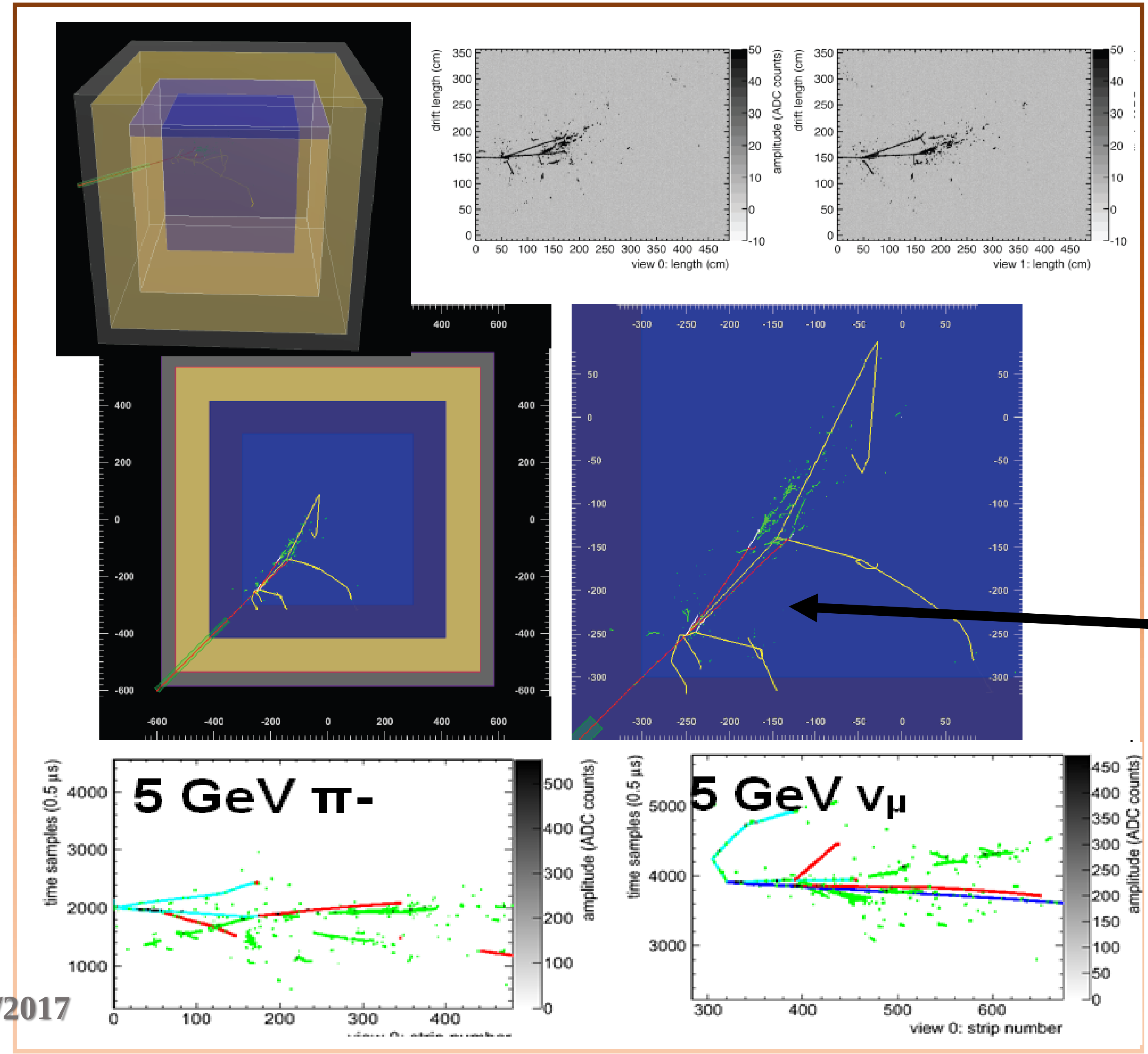
Beam line with all instrumentation integrated

Integration of beam-line DAQ within WA105 White-Rabbit time distribution system
Construction started → looking forward to commissioning

THE DUAL-PHASE protoDUNE

Simulation

5 GeV π+
in 6x6x6m³
dual-phase
liquid Argon



Physics program outlined in the TDR:

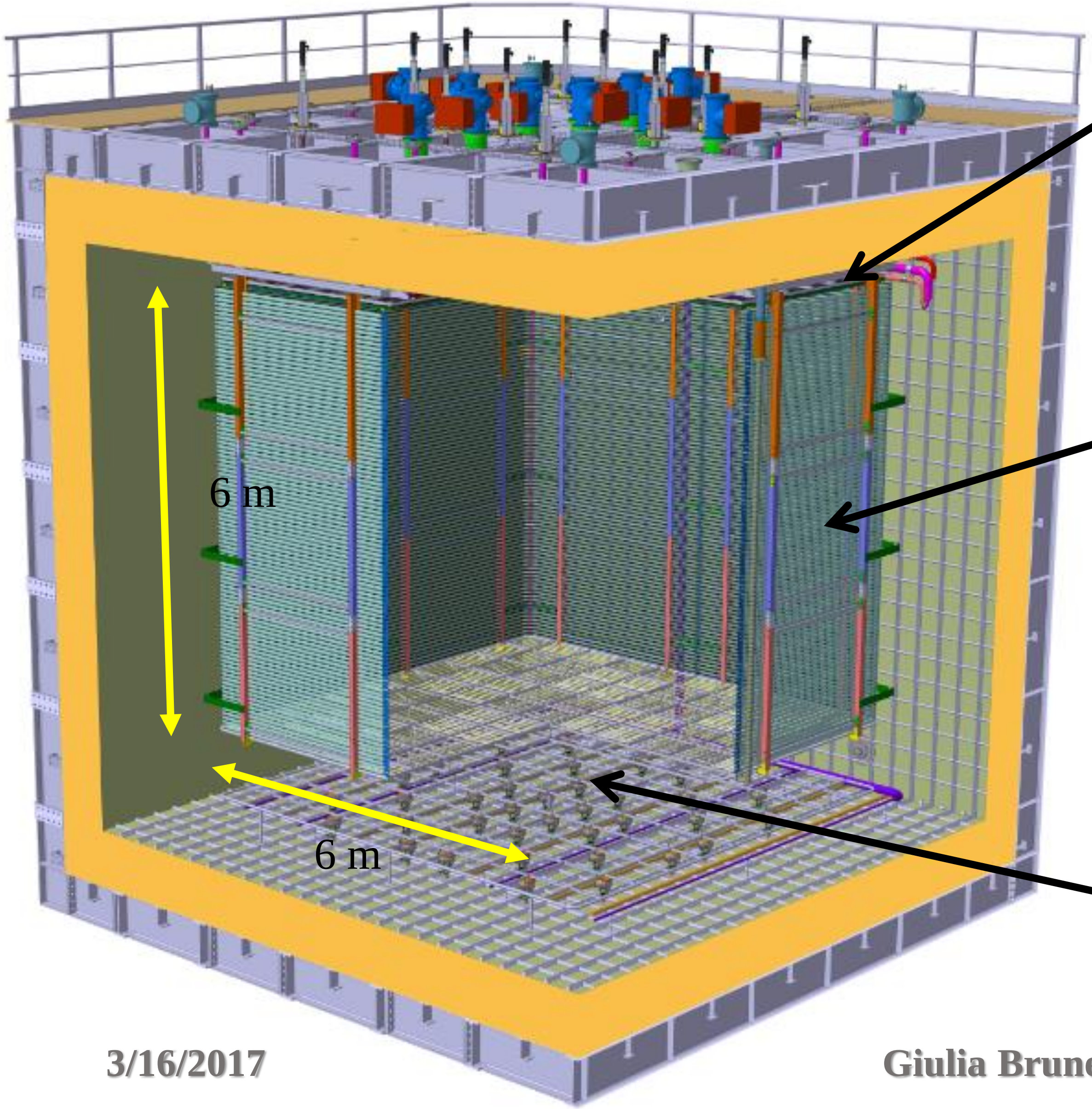
- em/hadronic calorimetry
- Cross section measurements
- π0 rejection
- Systematics for far detector

Hadronic showers fully contained in WA105

Reconstructed pion and neutrino interactions in DLAr

THE DUAL-PHASE protoDUNE

Full 3D electrostatic simulations completed for HV feedthrough, field-cage, cathode, ground grid



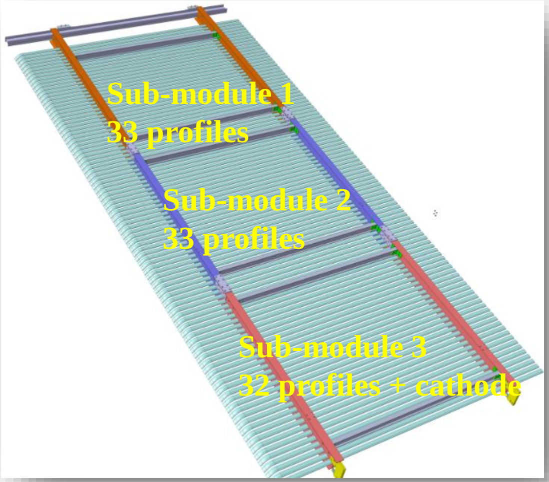
Charge Readout Planes (CRP): 3x3m^2 CRPs integrating the LEM-anode (50x50cm^2) and their suspension feedthroughs

- Assembly mechanism to ensure planarity ±0.5mm over the 3x3m^2 surface
- Minimal dead space in between CRPs

Field Cage:

- Common structural elements with SP
- 8 vertical modules, each one has 3 sub-modules

→ 98 modules with 60 mm pitch



Cathode:

- Transparent
- Resistive coating on 2 sides of plates
- Ground grid above PMTs
- Assembled in 4 modules

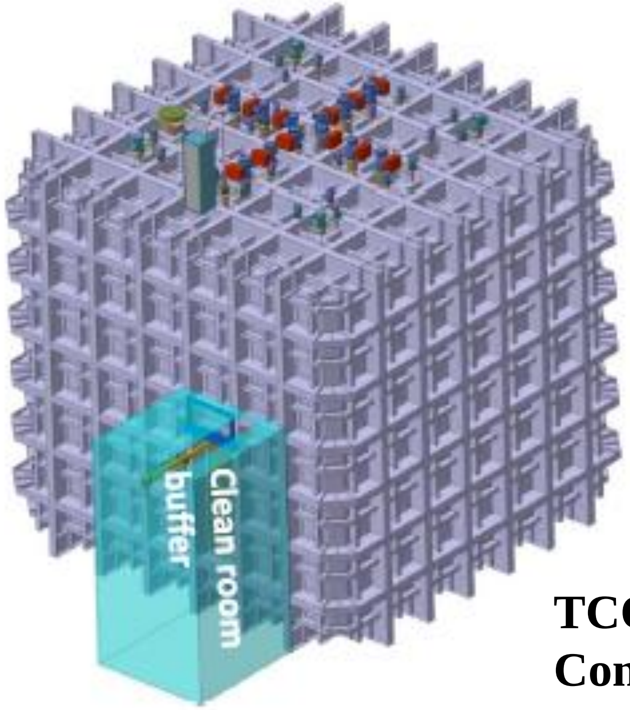
THE DUAL-PHASE protoDUNE

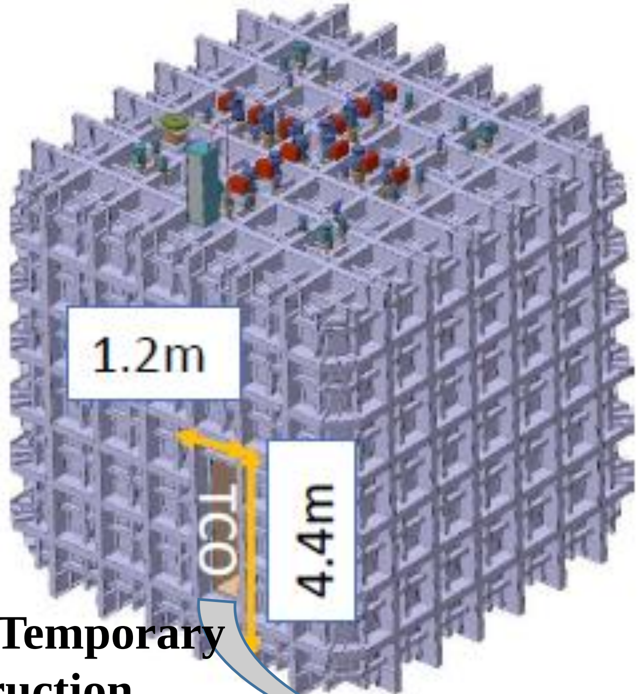
Wa105 Assembly

- First feedthroughs are installed
- The material for detector installation is brought to a clean room buffer and then TCO into the cryostat
- CRPs will be pre-assembled at CERN → then packed in a protective case → then brought in vertically via TCO

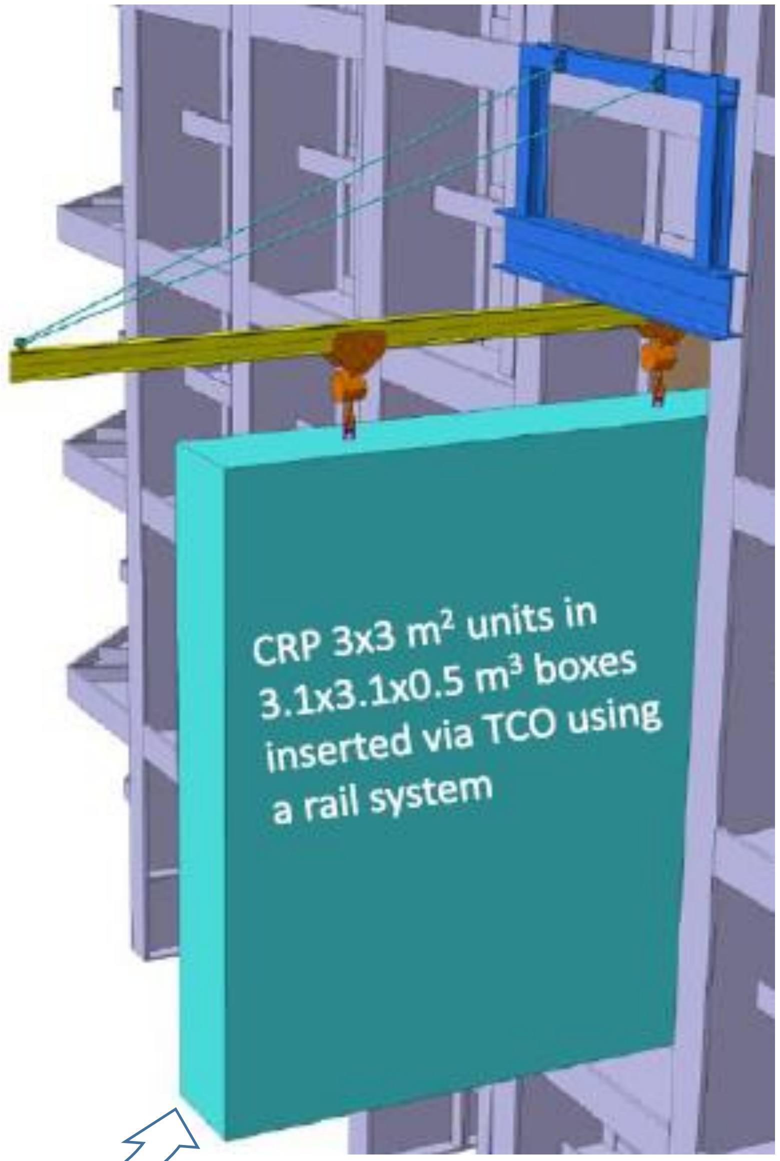
→ **installation sequence same as for 10kt DUNE**

CRP assembly at CERN in clean room requested in Bld185 → start Jan2017



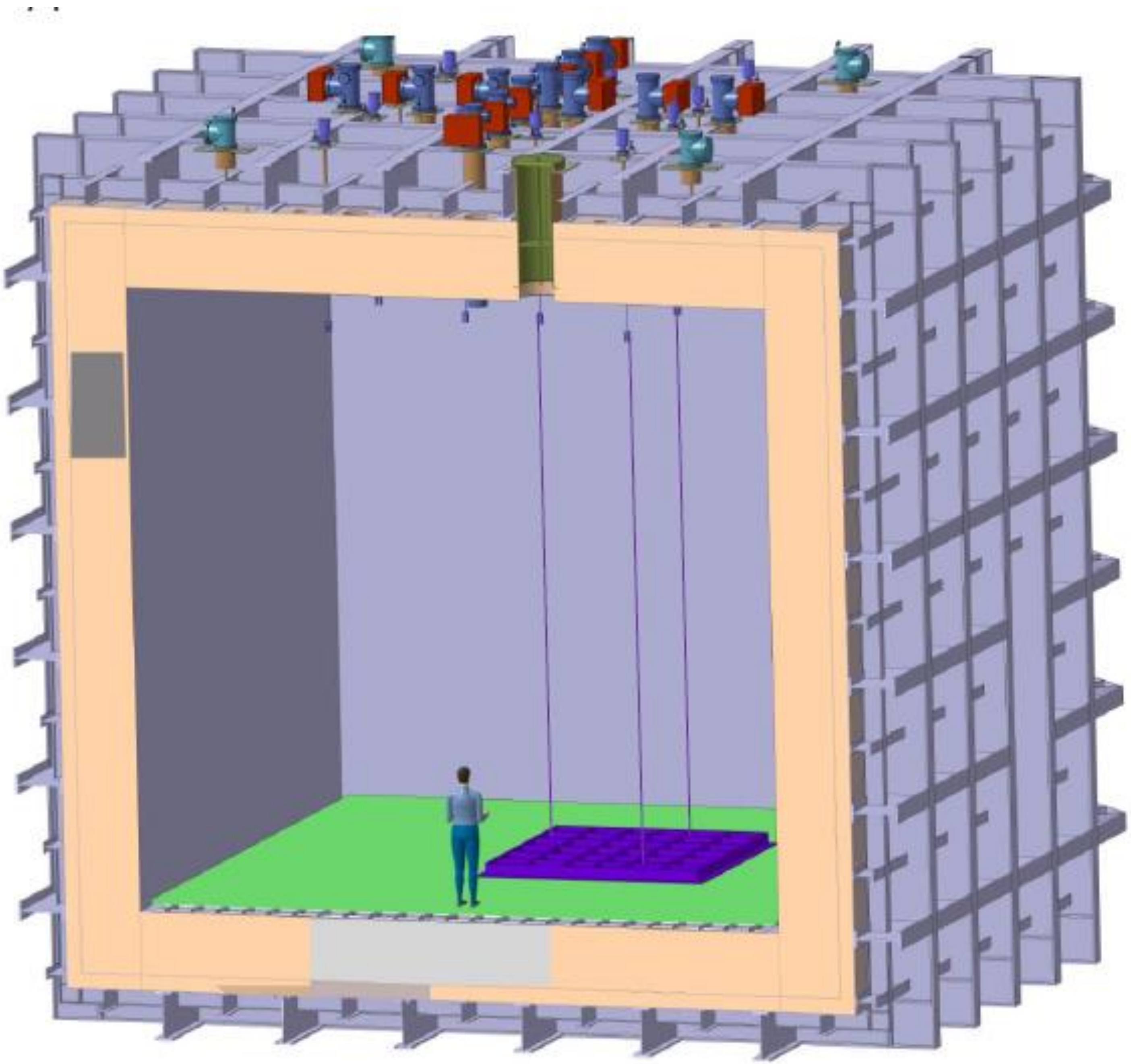


TCO=Temporary Construction Opening



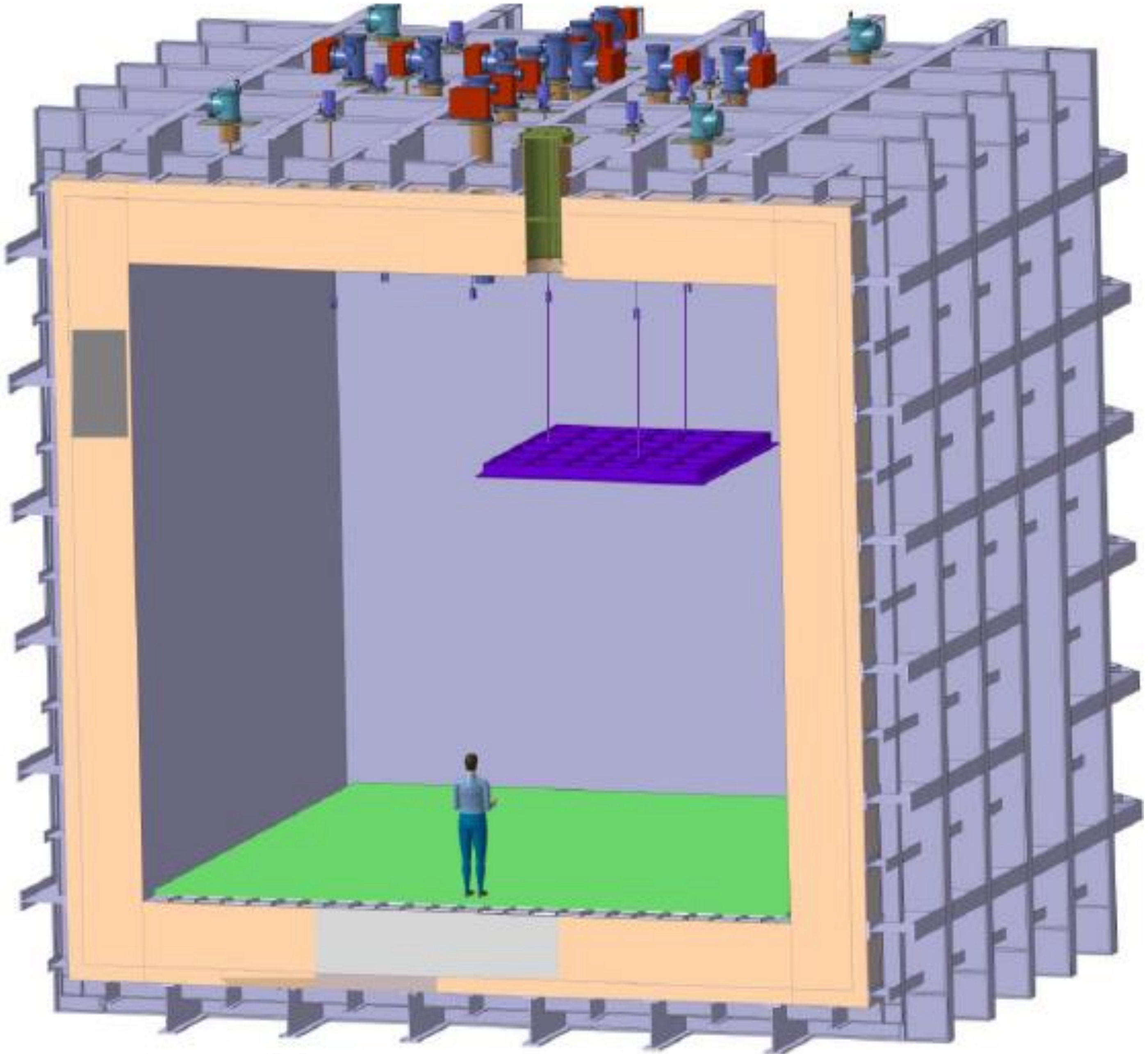
CRP 3X3 m²

- **First CRP assembled and in position**



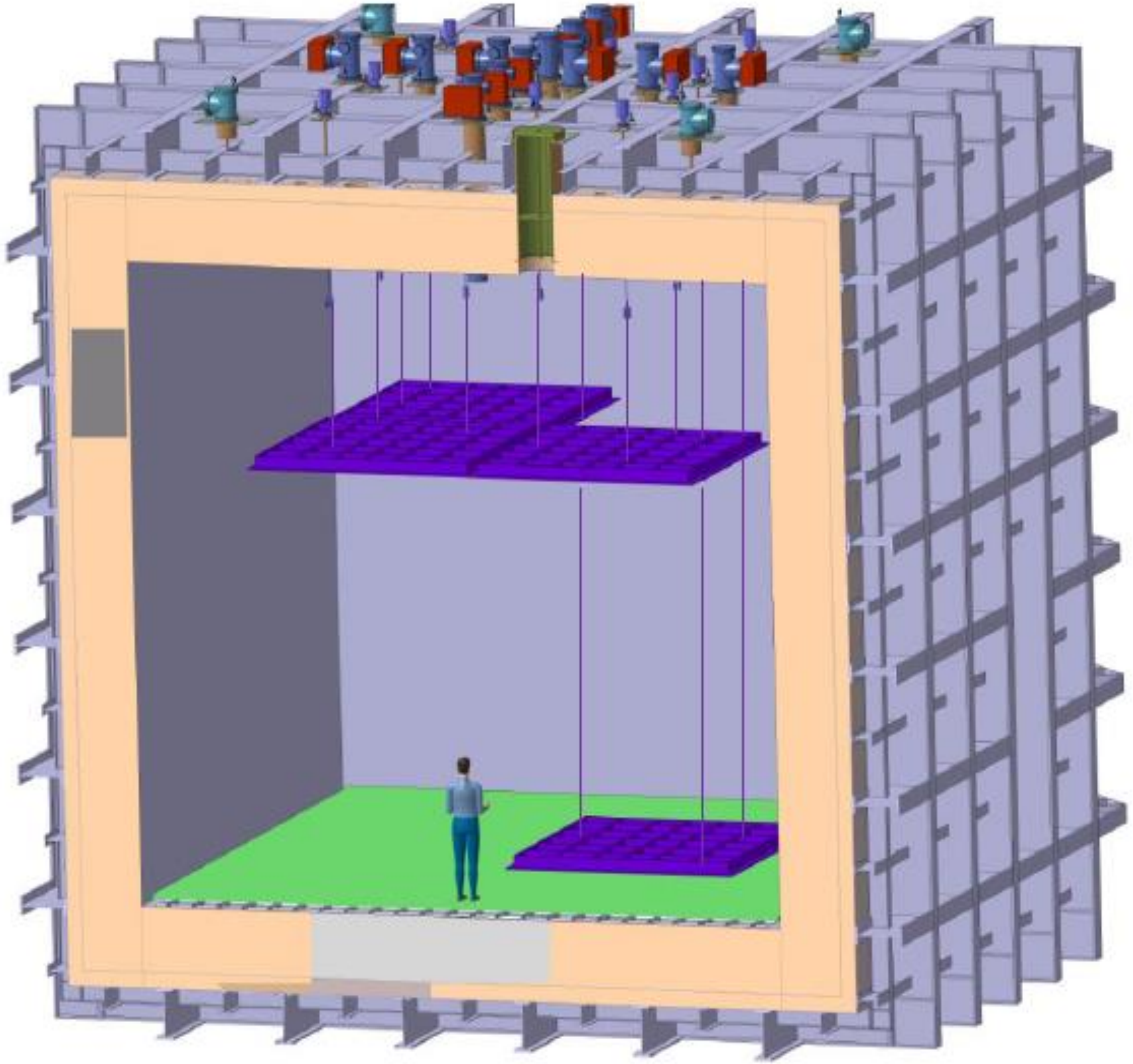
CRP 3X3 m²

- First CRP assembled and in position
- **CRP lifted**



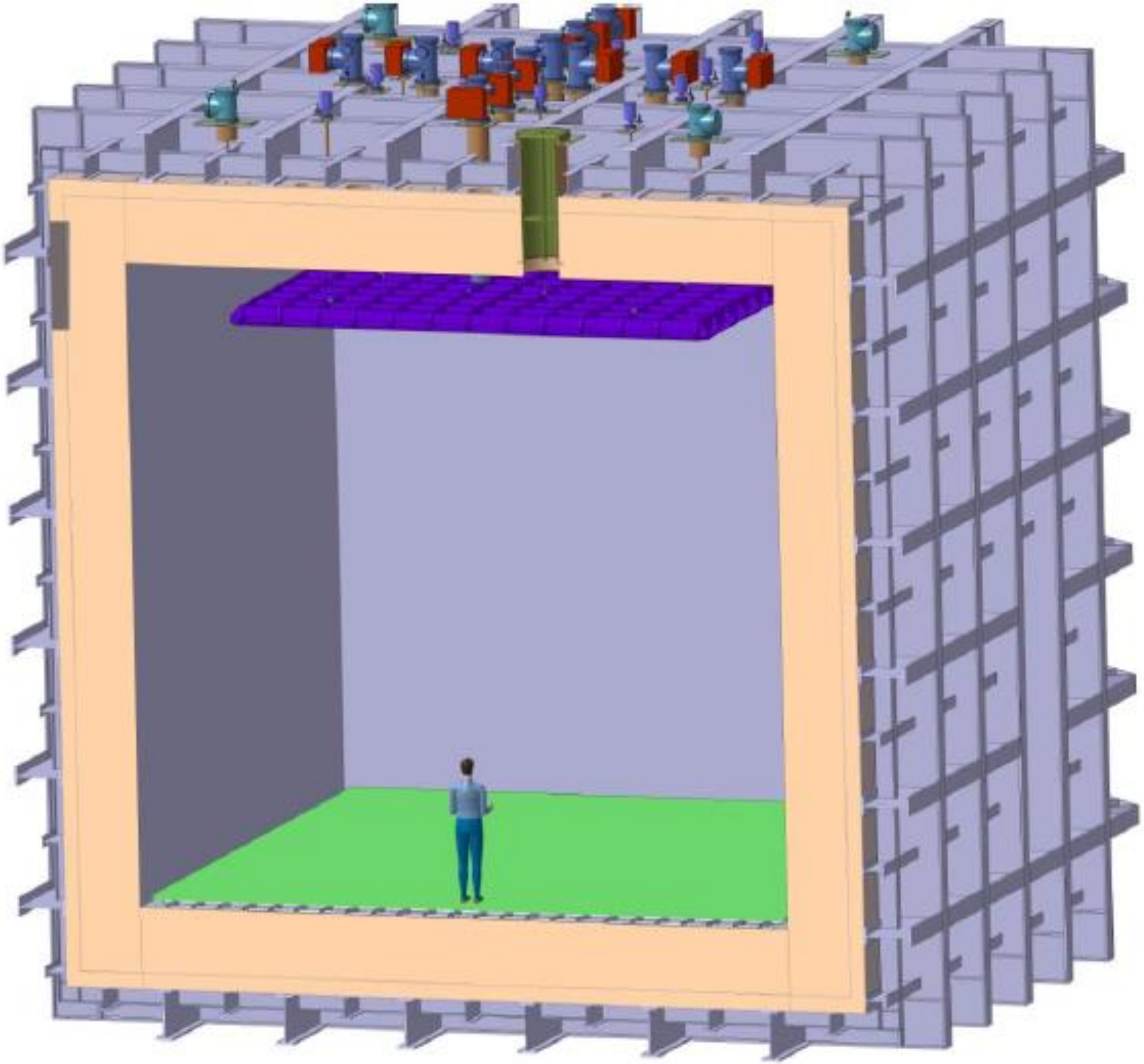
CRP 3X3 m²

- First CRP assembled and in position
- CRP lifted
- **Same procedure for the other CRPs**



CRP 3X3 m²

- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- **All CRPs fixed on nominal position**

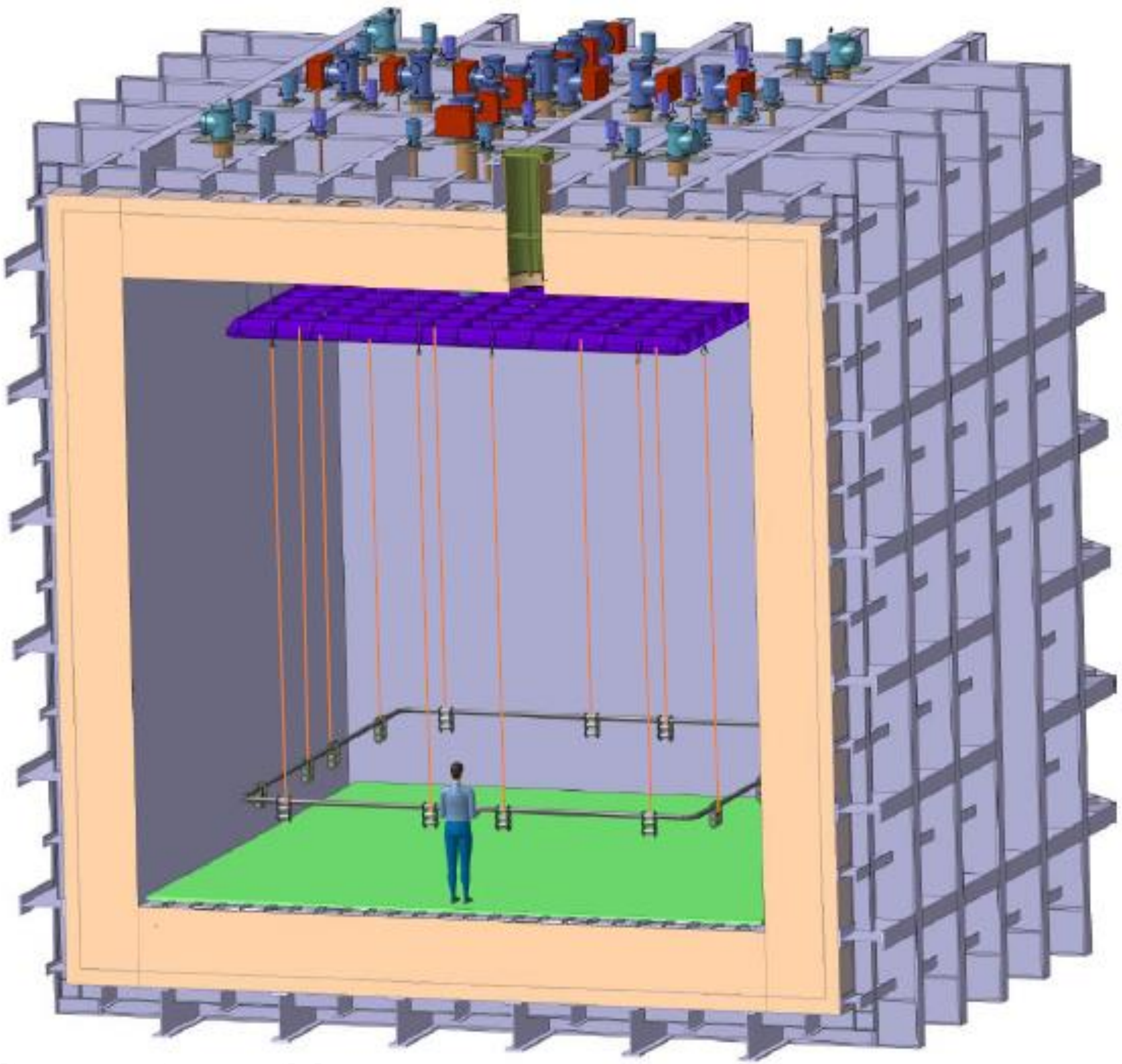


CRP 3X3 m²

- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- **First Field shaper installed**

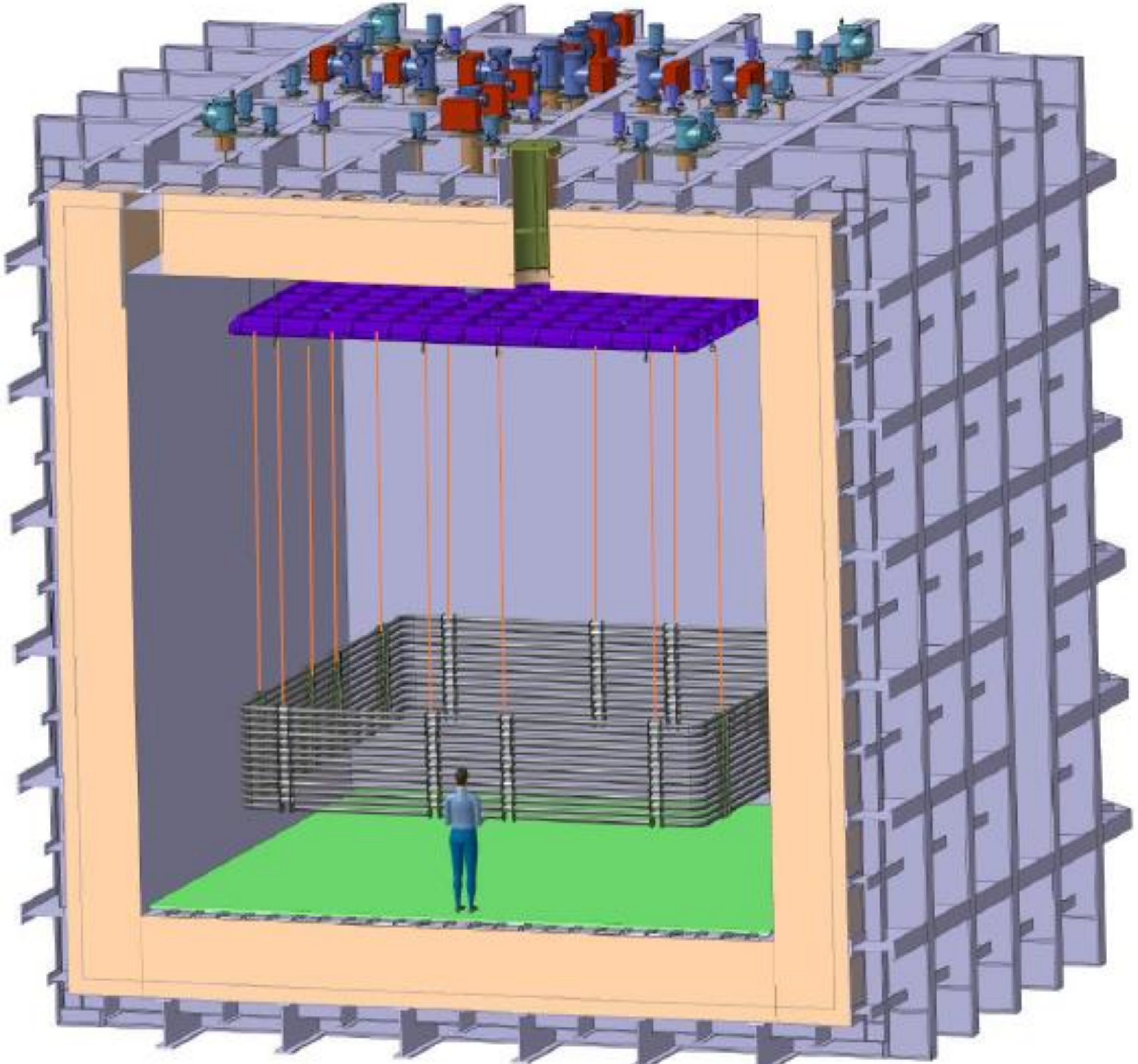


CRP 3X3 m²

- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- **Drift Cage is lifted as the field shaper are installed**



CRP 3X3 m²

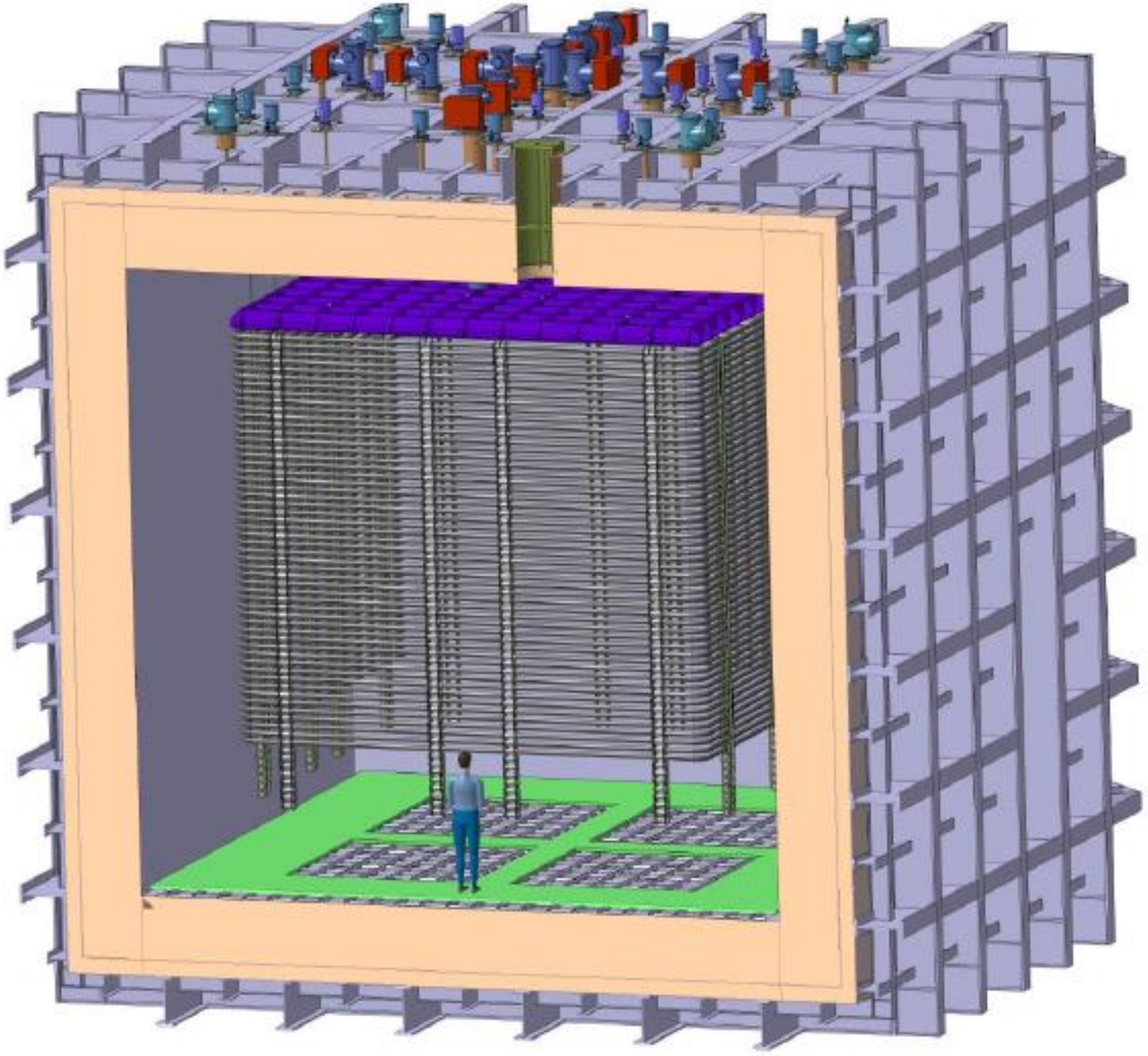
- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

- **Part of the temporary floor is removed**



CRP 3X3 m²

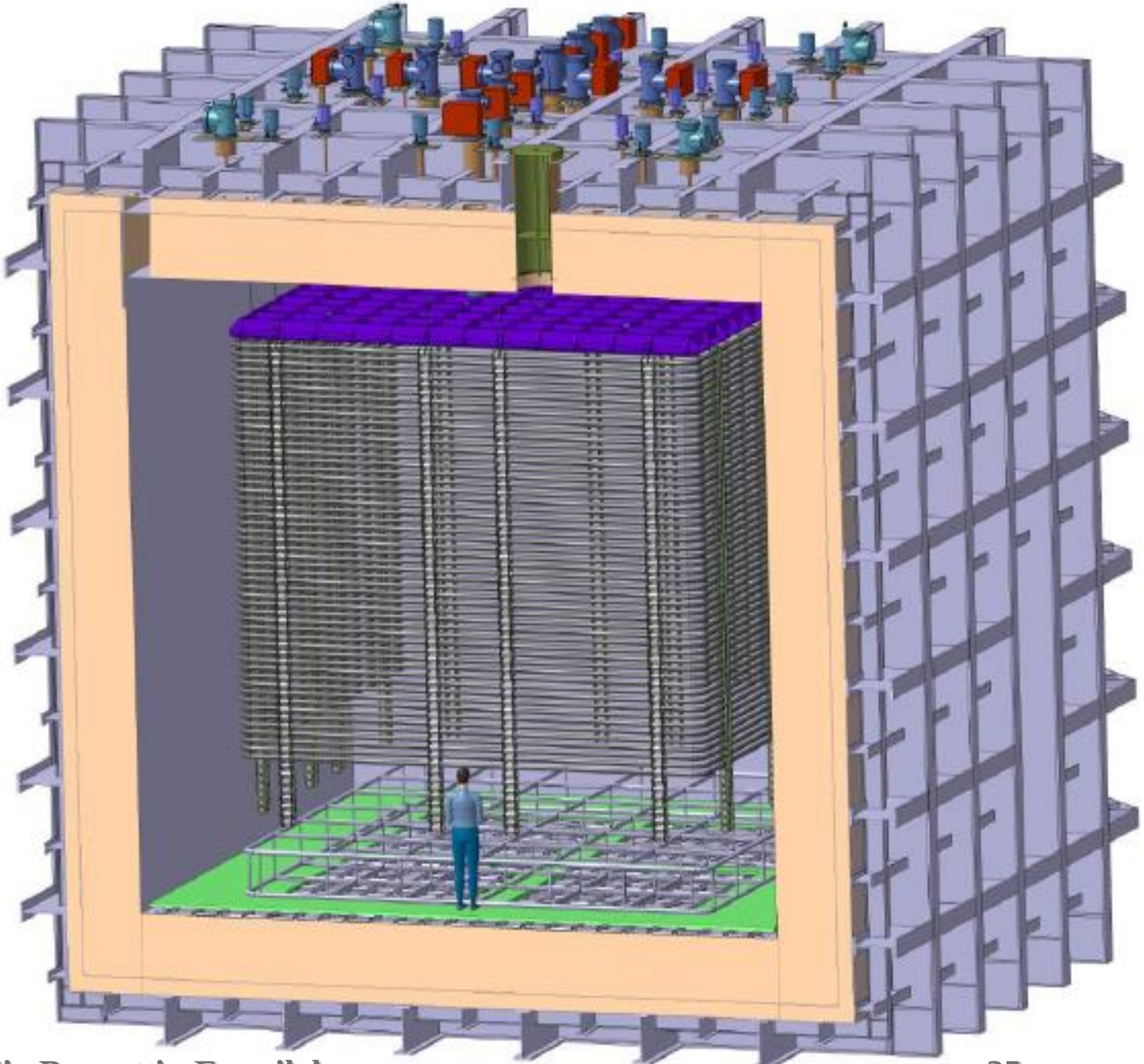
- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

- Part of the temporary floor is removed
- **Cathode structure assembled on the floor**



CRP 3X3 m²

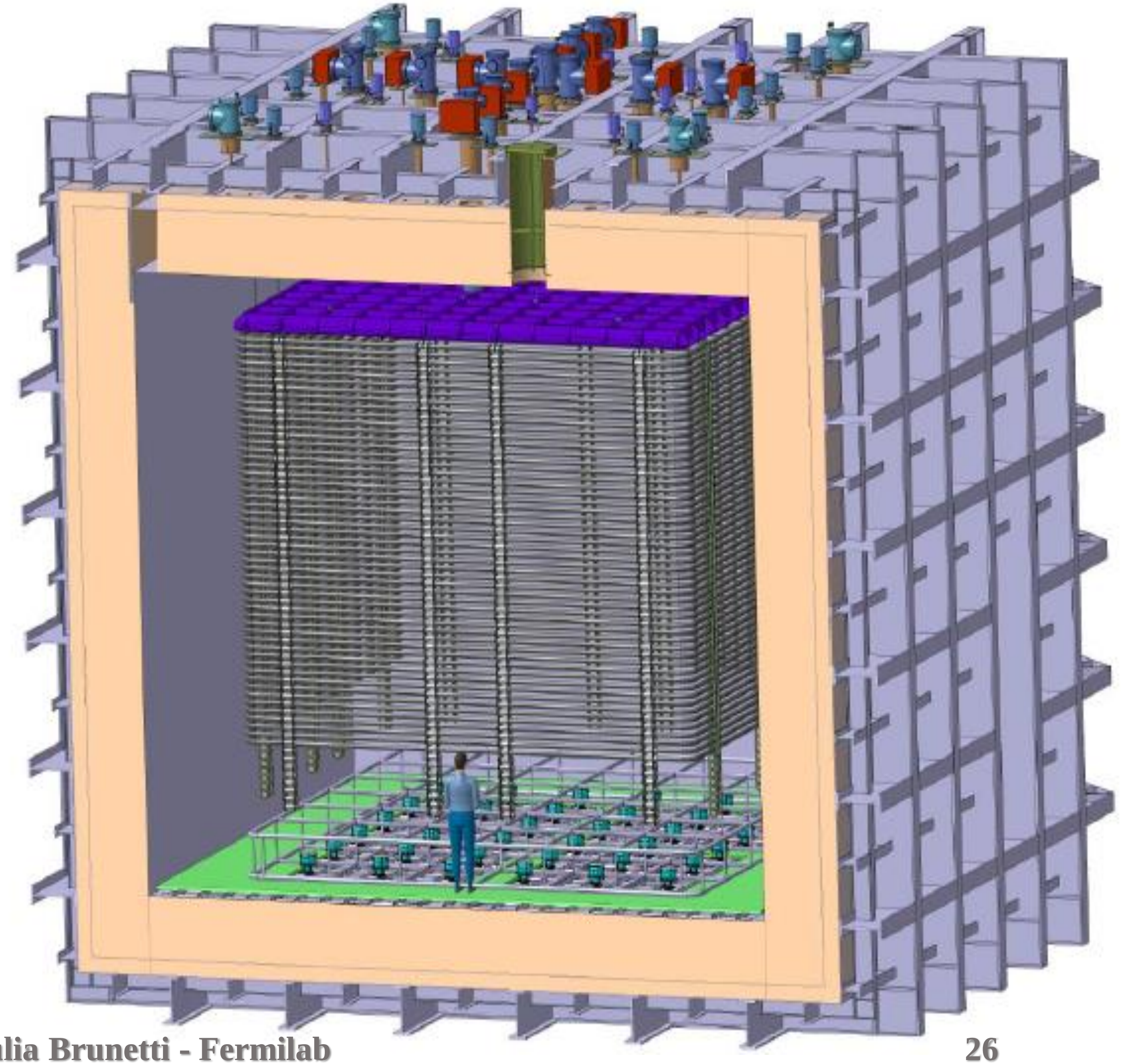
- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

- Part of the temporary floor is removed
- Cathode structure assembled on the floor
- **PMTs installation at the structure**



CRP 3X3 m²

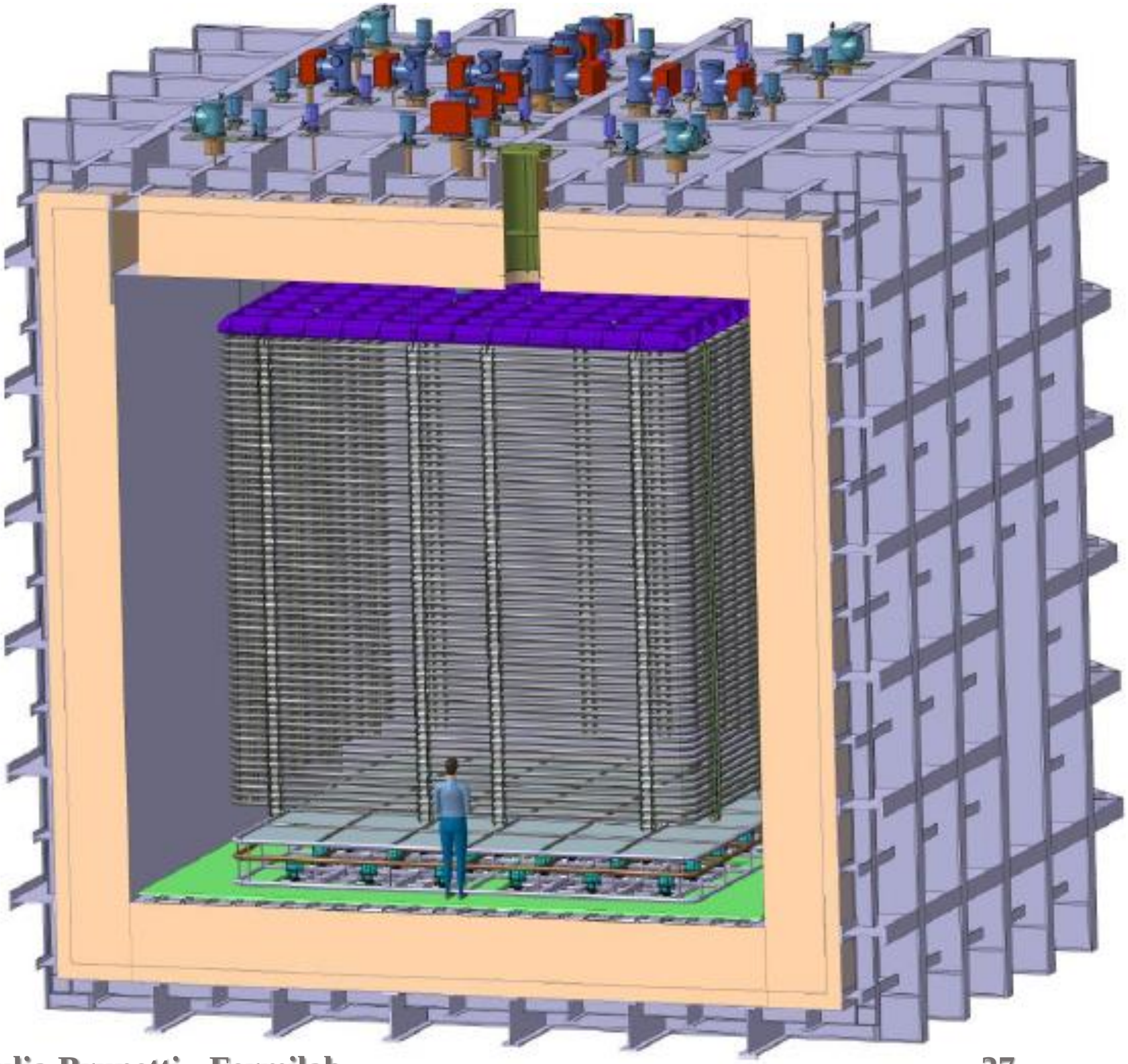
- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

- Part of the temporary floor is removed
- Cathode structure assembled on the floor
- PMTs installation at the structure
- **Installation of the last field shaper**



CRP 3X3 m²

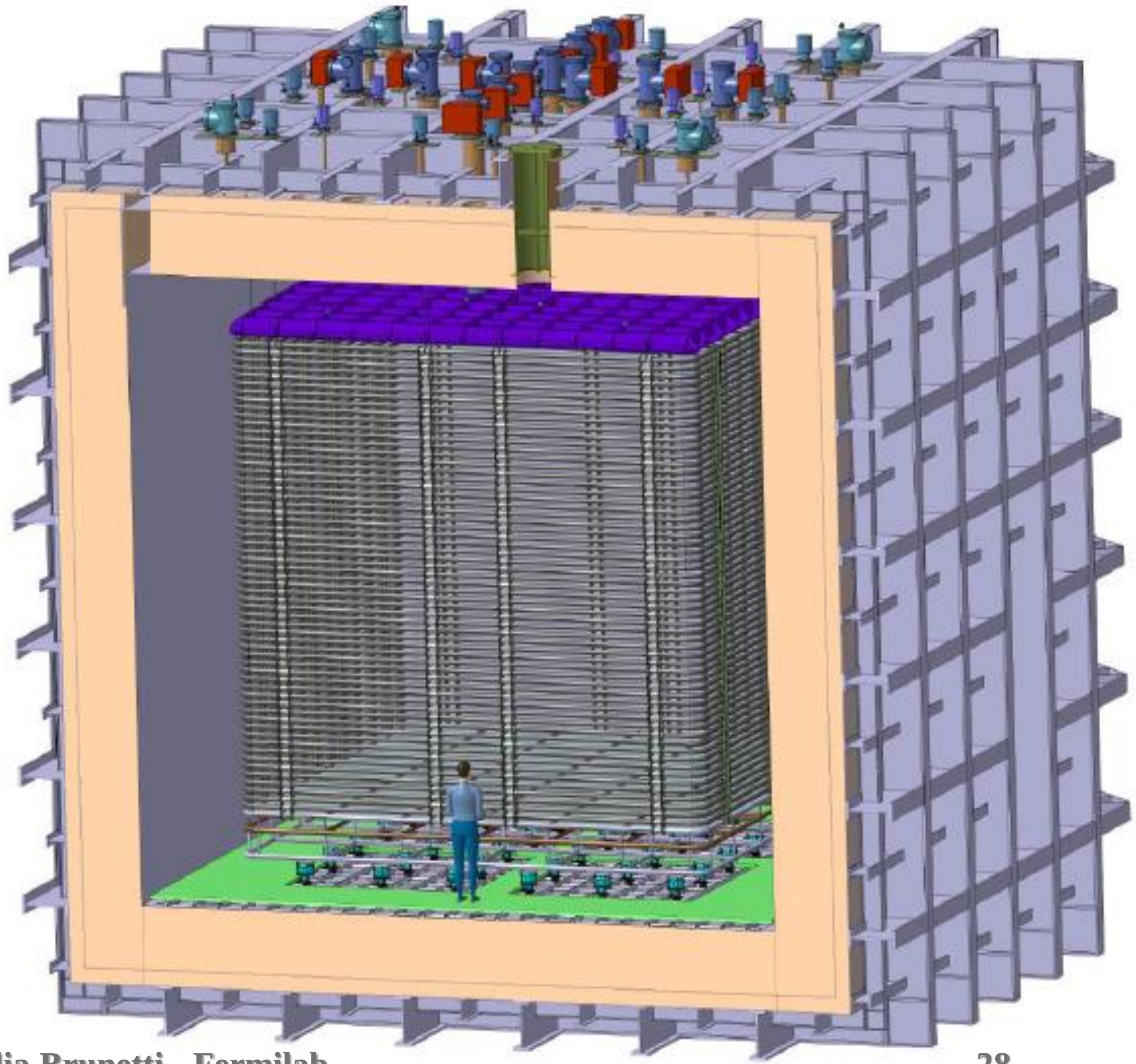
- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

- Part of the temporary floor is removed
- Cathode structure assembled on the floor
- PMTs installation at the structure
- Installation of the last field shaper
- **Cathode connected to the Drift Cage and lifted**



CRP 3X3 m²

- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

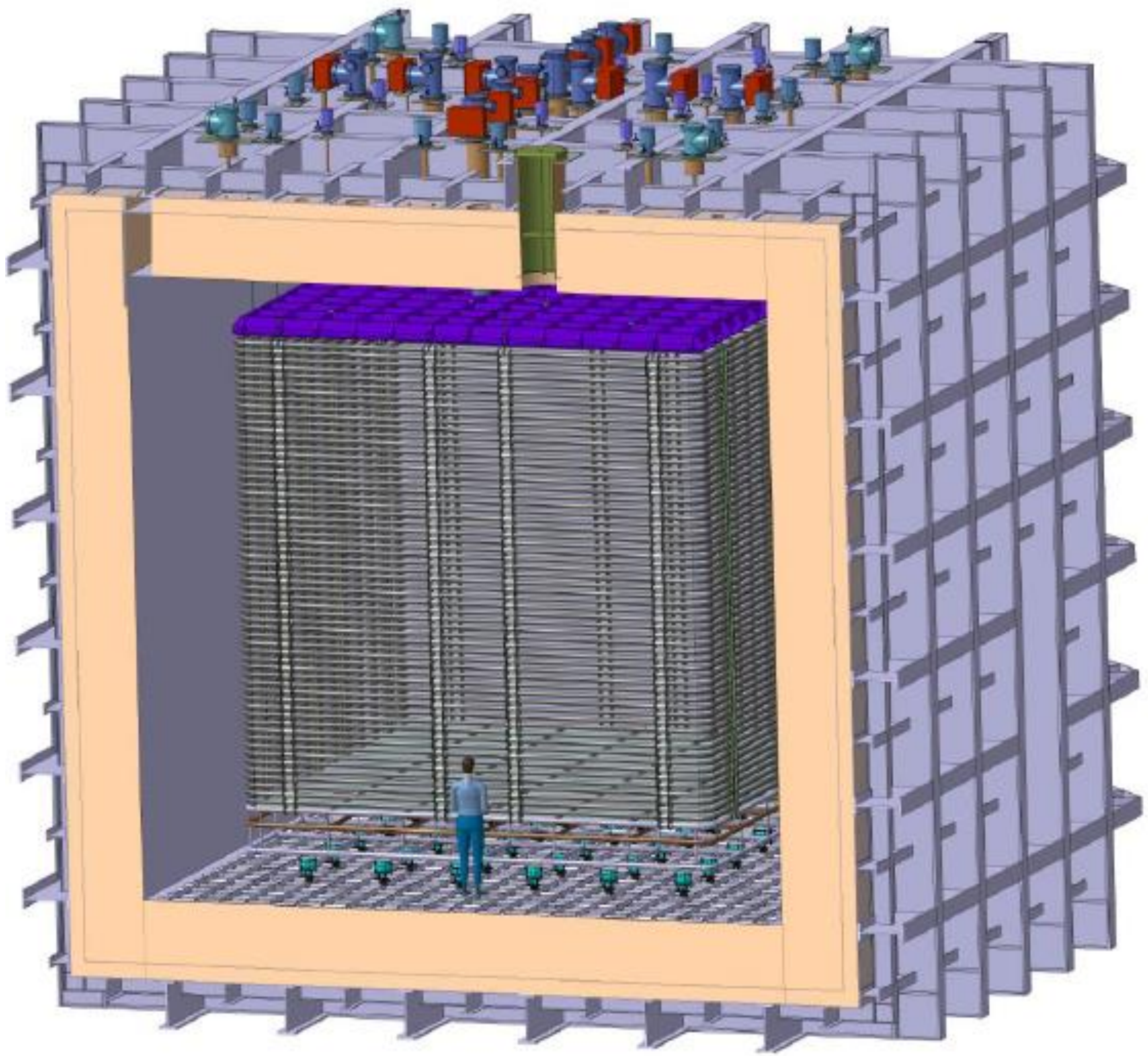
- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

- Part of the temporary floor is removed
- Cathode structure assembled on the floor
- PMTs installation at the structure
- Installation of the last field shaper
- Cathode connected to the Drift Cage and lifted

Removal of Temporary Assembly Floor

- **Temporary Assembly floor removed**



CRP 3X3 m²

- First CRP assembled and in position
- CRP lifted
- Same procedure for the other CRPs
- All CRPs fixed on nominal position

Field Cage

- First Field shaper installed
- Drift Cage is lifted as the field shaper are installed

Cathode and PMTs

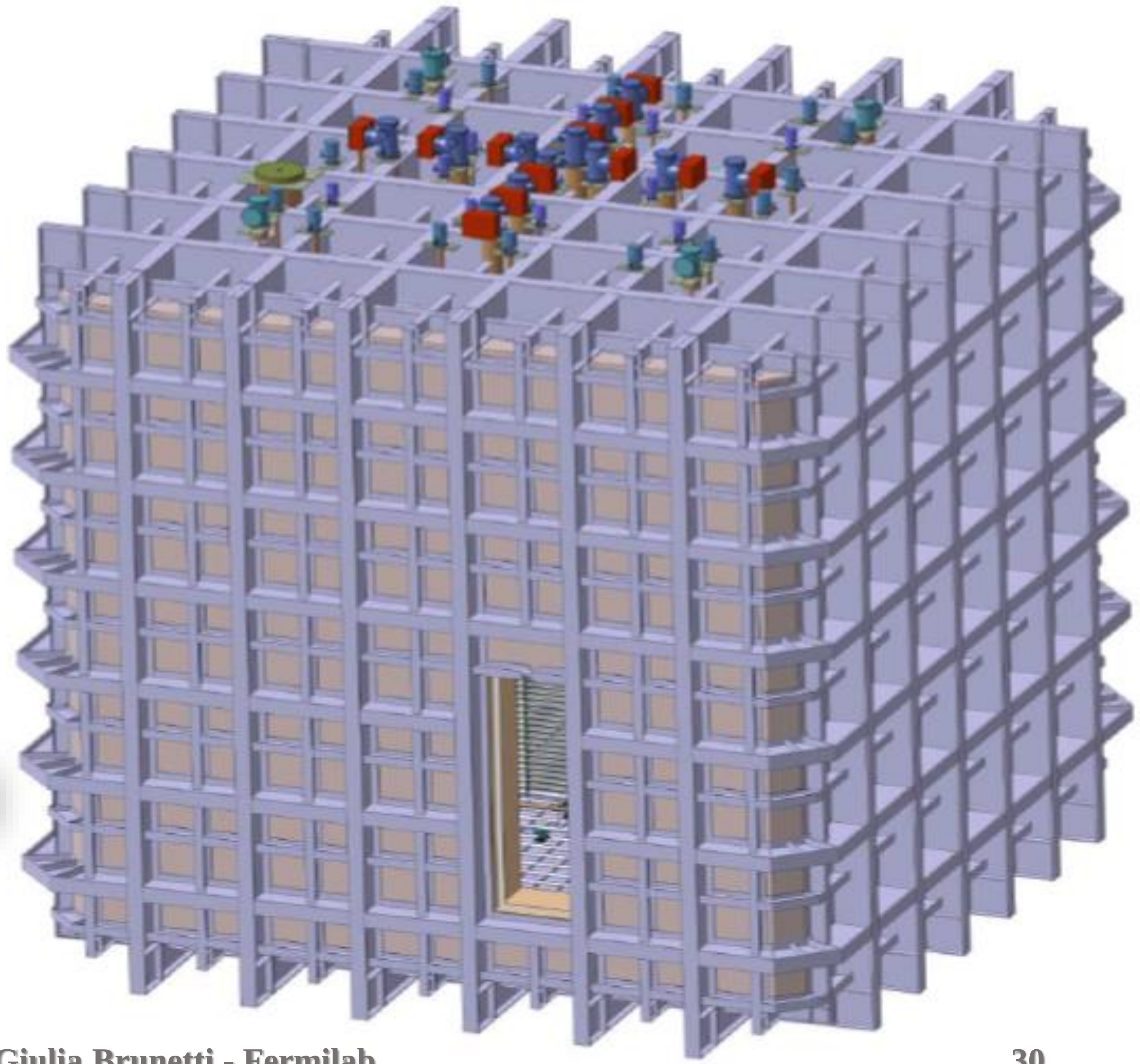
- Part of the temporary floor is removed
- Cathode structure assembled on the floor
- PMTs installation at the structure
- Installation of the last field shaper
- Cathode connected to the Drift Cage and lifted

Removal of Temporary Assembly Floor

- Temporary Assembly floor removed

Closure of the TCO

- **Membrane and TCO closed**



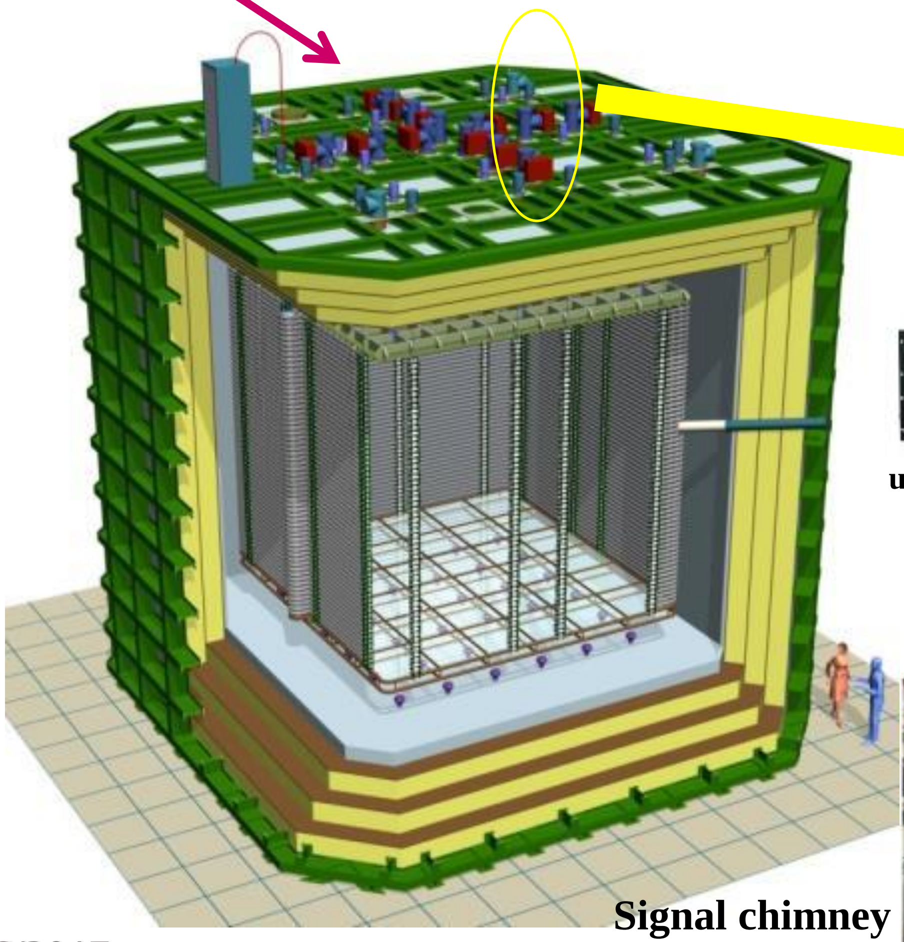
THE DUAL-PHASE protoDUNE – Front –End electronics

Double-phase charge readout is at the top of the detector → FULL ACCESSIBILITY

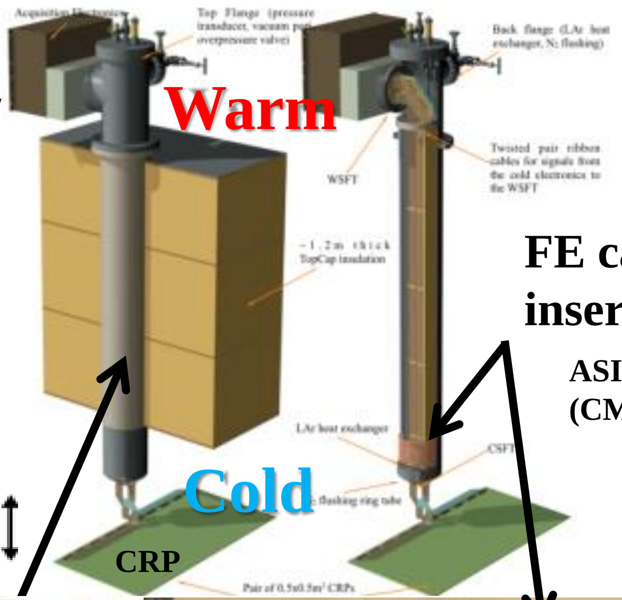
- **Digital electronics at warm on the tank deck:**
- Architecture based on μTCA standard
- 1 crate/signal chimney, 640 channels/crate

→ 12 μTCA crates

- **Cryogenic ASIC amplifiers externally accessible:**
- Working at 110K at the bottom of the signal chimneys
- Cards fixed to a plug accessible from outside

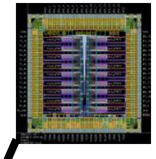


uTCA crate

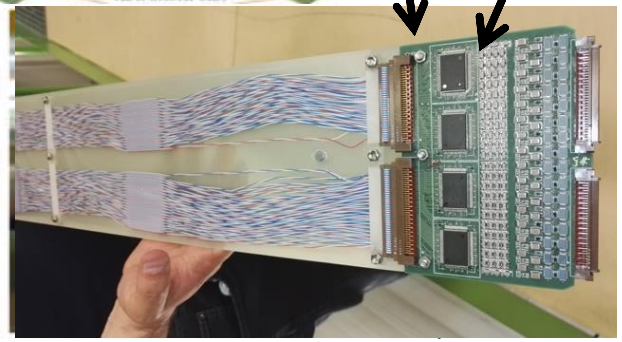


FE cards mounted on insertion blades

ASICs 16 ch. (CMOS 0.35 um)



Signal chimney



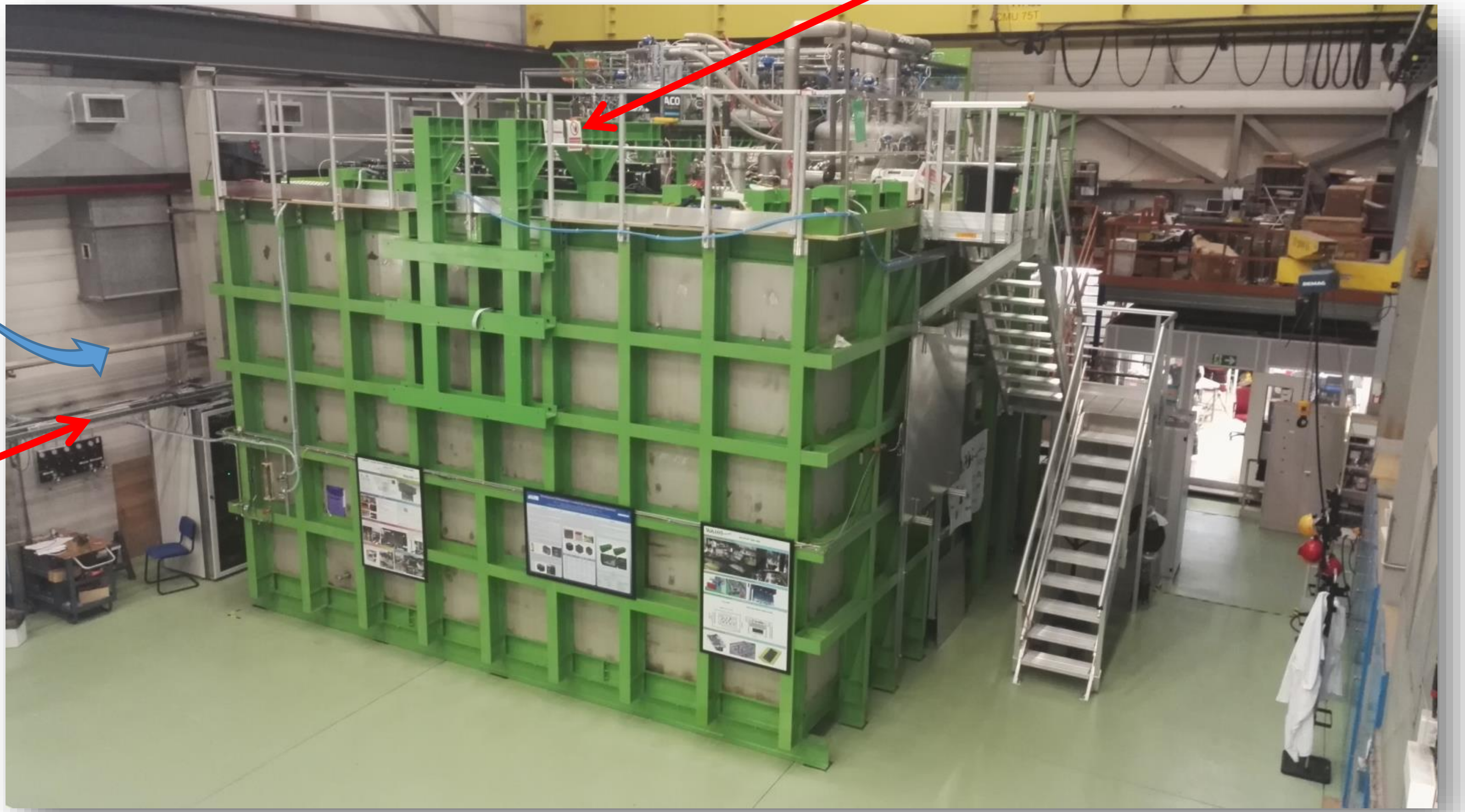
THE DUAL-PHASE protoDUNE – Front –End electronics

- Cost-effective and fully accessible
- R&D since 2006 → now in production for the 6x6x6
- FE electronics inside chimneys, cards accessible from outside
- Distance cards-CRP < 50 cm
- **1280 channels installed on 3x1x1**

Signal Chimneys and μTCA crates

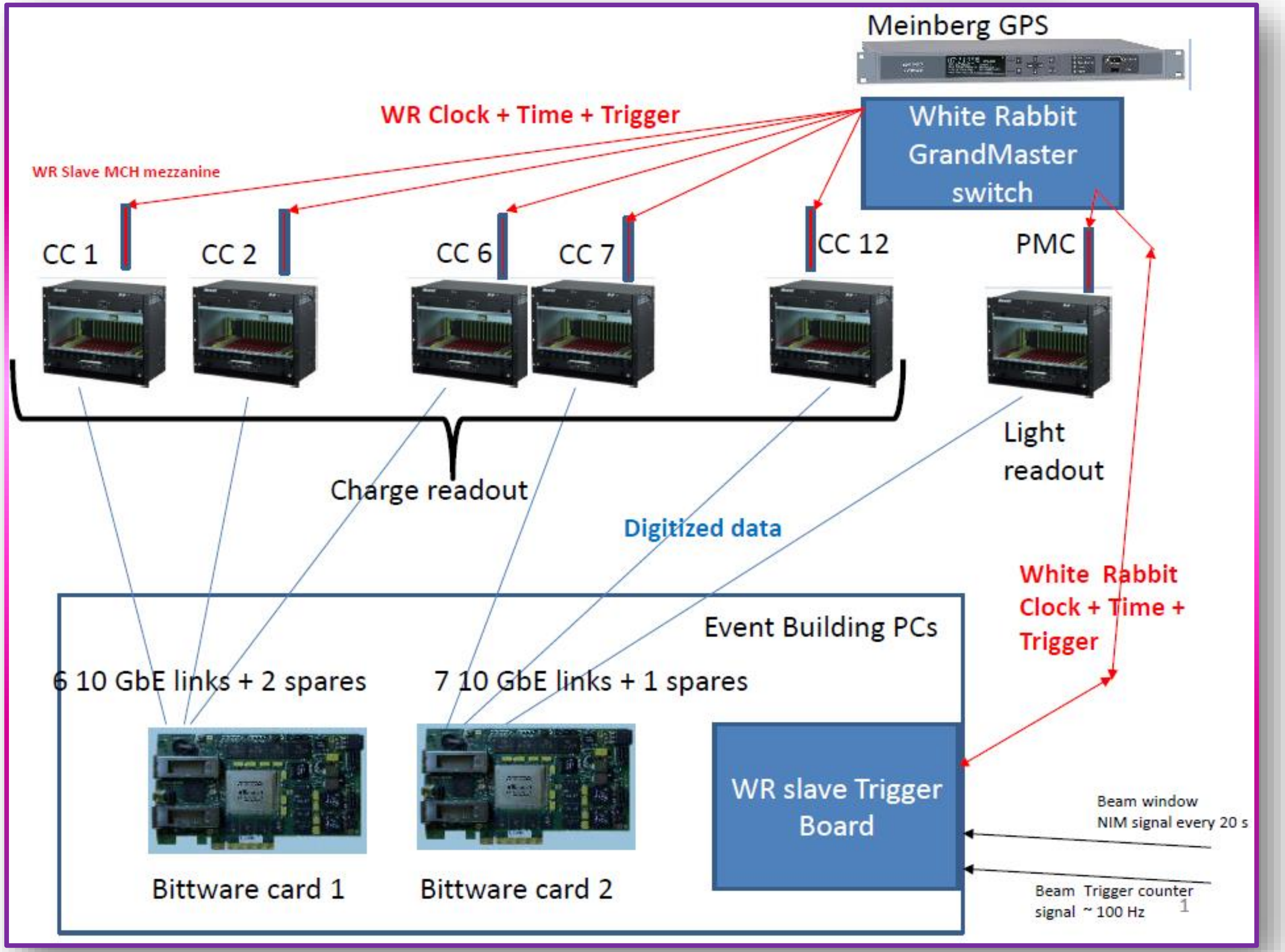
4 μTCA
+ Slow Control

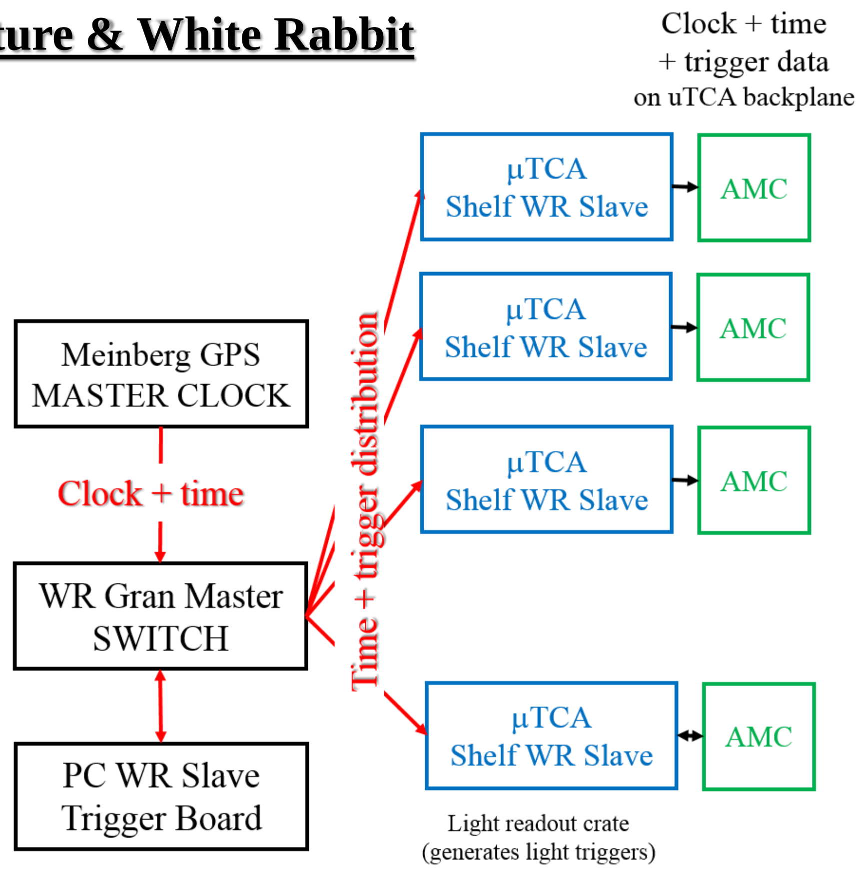
Event builder, network,
GPS/White Rabbit GM,
WR Trigger PC



THE DUAL-PHASE protoDUNE – DAQ Architecture & White Rabbit

DAQ architecture integrated with « White Rabbit » (WR) Time and Trigger distribution network





- WR is an evolution of synchronous Ethernet + PTP
- Accurate at sub-ns level, enough to align the 400ns samples
- The beam trigger can be timestamped on the PC trigger board and broadcasted to the microTCA crates via the WR distribution network

Plans for ProtoDUNE dual-phase
Dario Autiero, DUNE Collaboration Meeting, January 2017

Conclusions

THE DUAL-PHASE "proto" protoDUNE

- ***The dual-phase design provides many appealing aspects*** in improving the detector performance and reducing its construction costs. **Long standing efforts have been spent in this direction during the last 10 years and are now culminating in a large scale implementation with the 6x6x6 detector operation in the CERN North Area.**

- Remaining aspects of the 6x6x6 executive design (CRPs, Field-Cage, Anode) were completed by the end of November 2016 and are now ready for production. Other parts (FE and DAQ electronics, Slow Control, PMTs, HV, Cosmic Ray Triggers) have already entered in production. The beamline layout and instrumentation have also been defined and construction started.

- We are looking forward to starting the installation work (pending the availability of the Icarus clean room in hall 185 and access to the cryostat) and to the **detector exploitation in 2018 with the collection of about 100M of beam triggers**

- **The activity on the 3x1x1 pilot detector has been extremely useful in order to reach an advanced state of prototyping and costs assessment of most of the components for the 6x6x6** and to anticipate legal and procurement problems. The 3x1x1 assembly was completed in the fall 2016 and its cryogenic system in December. The operation of the 3x1x1 will also allow for testing and optimizing the design of the online storage/data processing system, having a subset of the system already available.

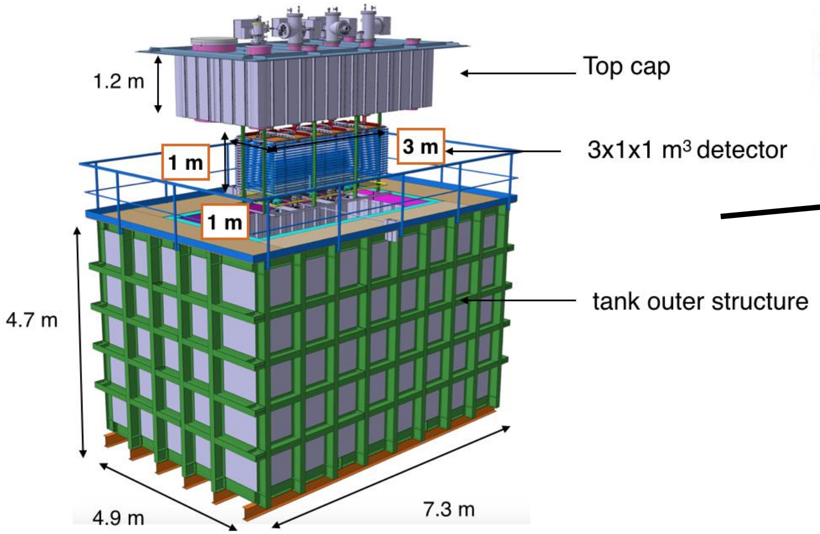
THE DUAL-PHASE "proto" protoDUNE – The 3x1x1

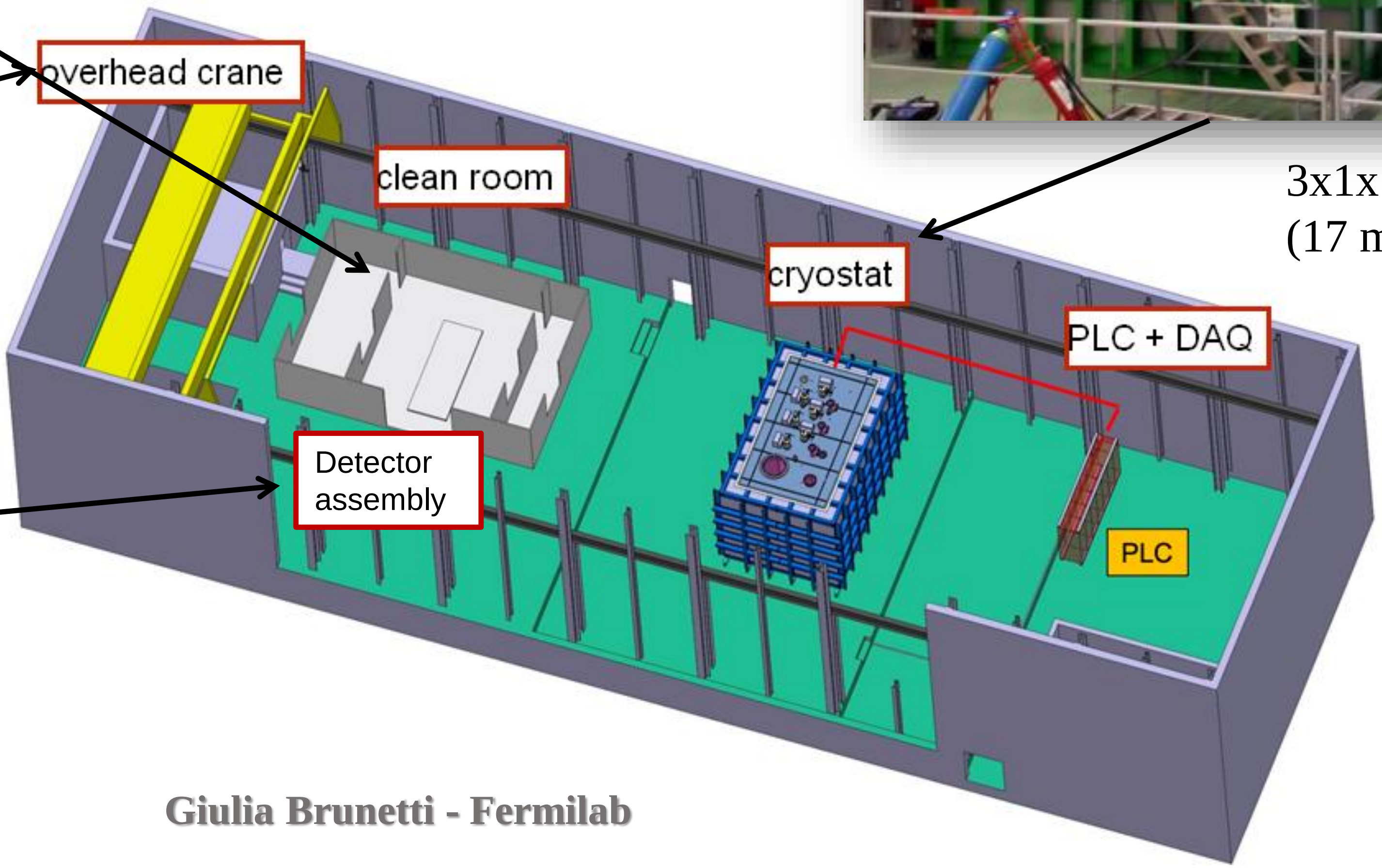
25-ton dual-phase Lar TPC pilot prototype at CERN building 182

Clean room for LEM tests +
CRP production and assembly

3x1x1 cryostat
(17 m^3)

Crane used to lift up the detector and
bring it to the cryostat

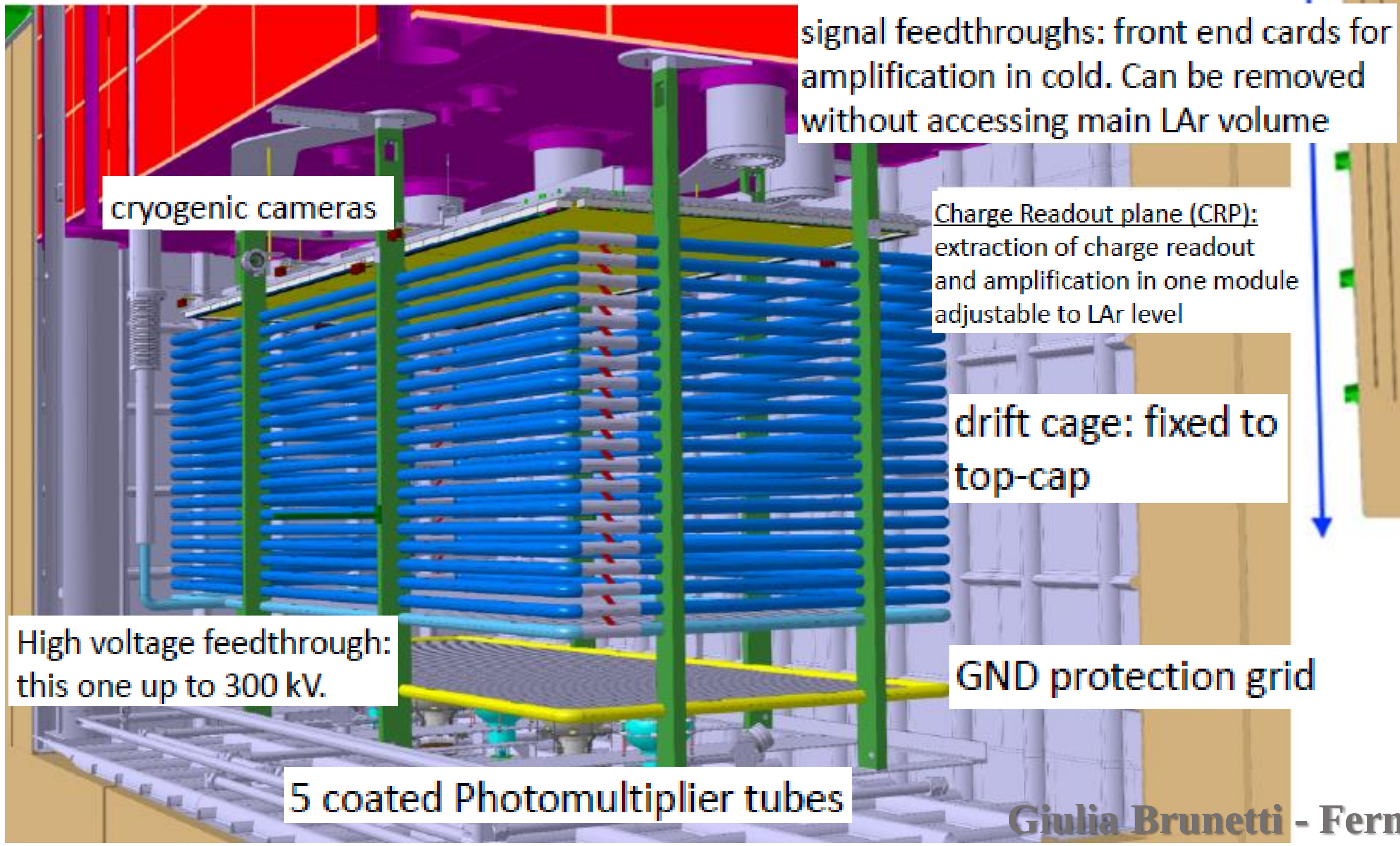


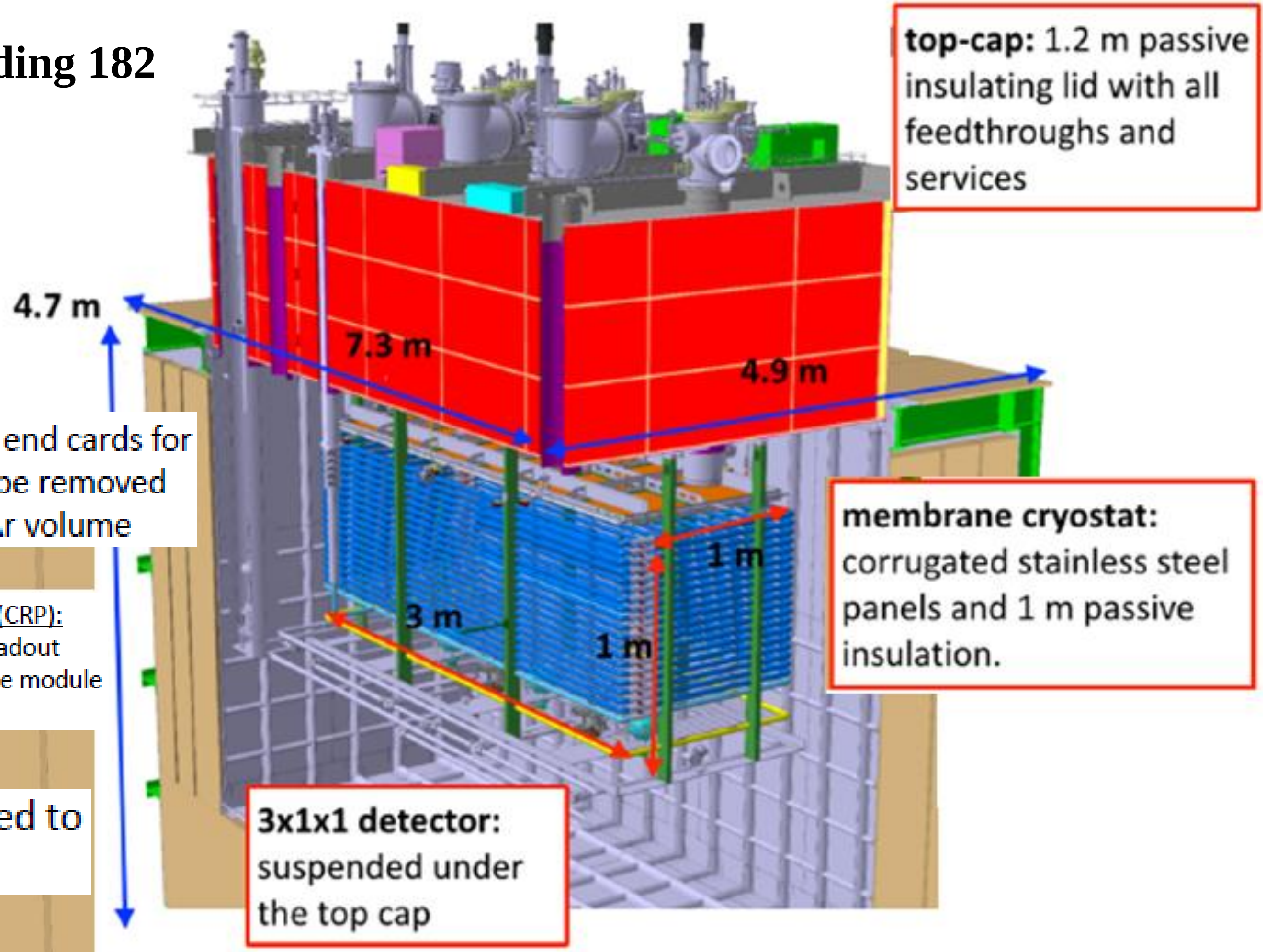


THE DUAL-PHASE "proto" protoDUNE – The 3x1x1

25-ton dual-phase Lar TPC pilot prototype at CERN building 182
Charge readout area =3x1 m2
Drift 1m

1m high field cage made by 20 field shapers placed at a constant spacing of 50mm + metallic grid cathode





See **Status of WA105 3x1x1m3 prototype**
Sebastien Murphy, DUNE Collaboration Meeting, January 2017

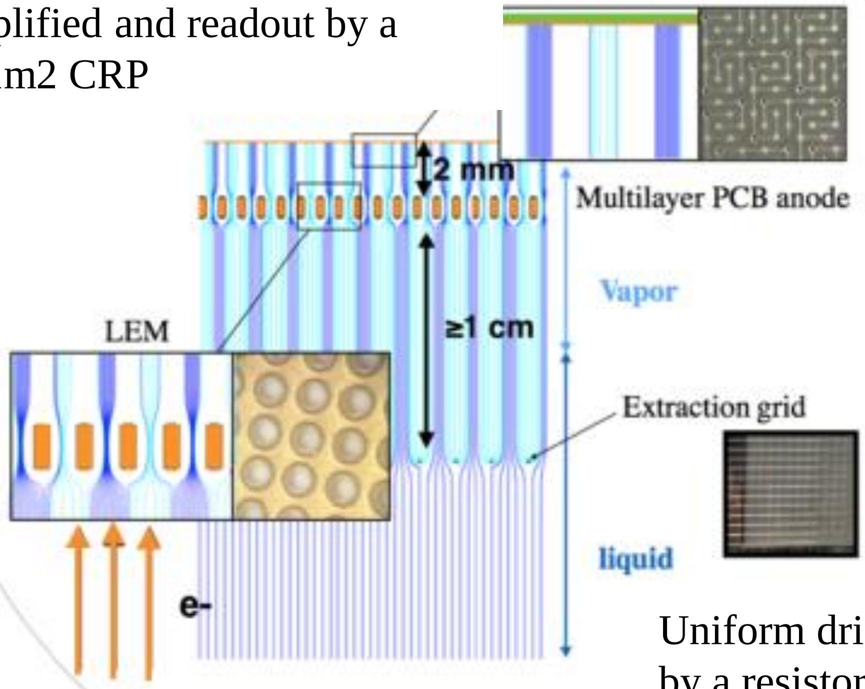
THE DUAL-PHASE "proto" protoDUNE – The 3x1x1

25-ton dual-phase Lar TPC pilot prototype at CERN building 182

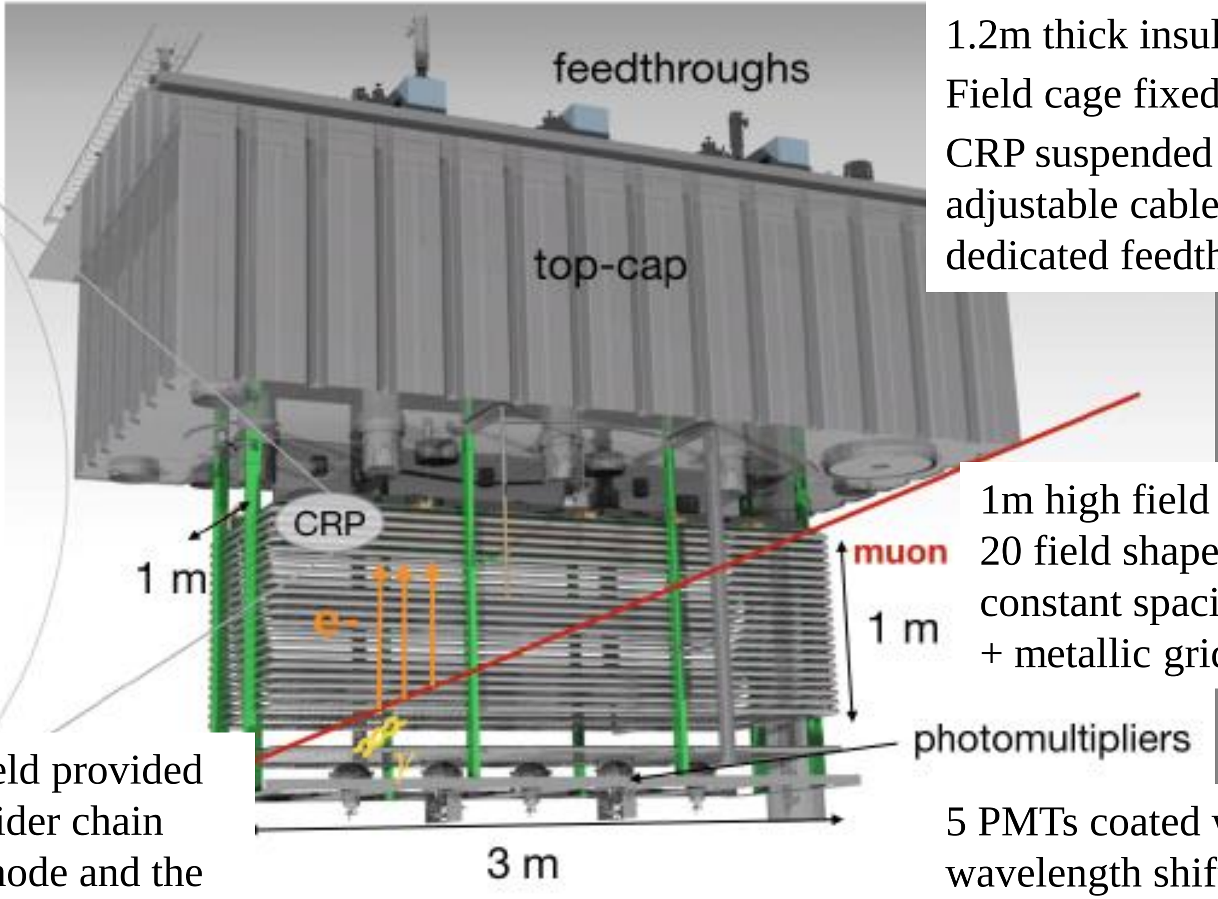
Charge readout area =3x1 m2

Drift 1m

Drifting charges are extracted to the gas phase where they are amplified and readout by a 3x1m2 CRP



Uniform drift field provided by a resistor divider chain between the cathode and the top field shaper



Entire detector hung under 1.2m thick insulatind top-cap

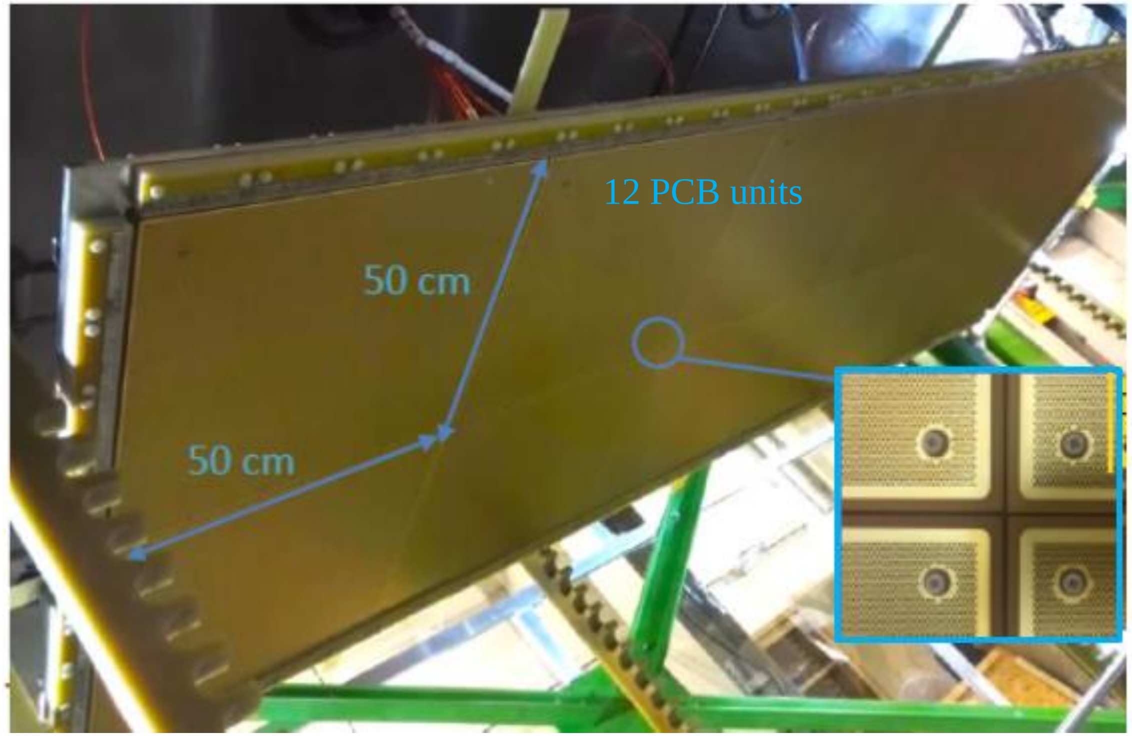
Field cage fixed by 8 bars

CRP suspended with 3 adjustable cables inserted in dedicated feedthroughs

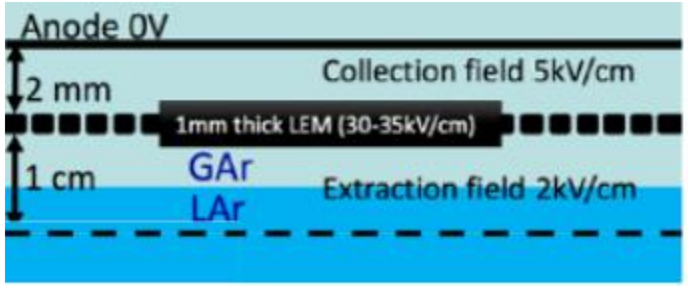
1m high field cage made by 20 field shapers placed at a constant spacing of 50mm + metallic grid cathode

5 PMTs coated with wavelength shifter under the cathode

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
The Charge Readout Plane (CRP)



A "multilayer sandwich"
The CRP consists of
- the 2D anode
- the LEM
- the extraction grid



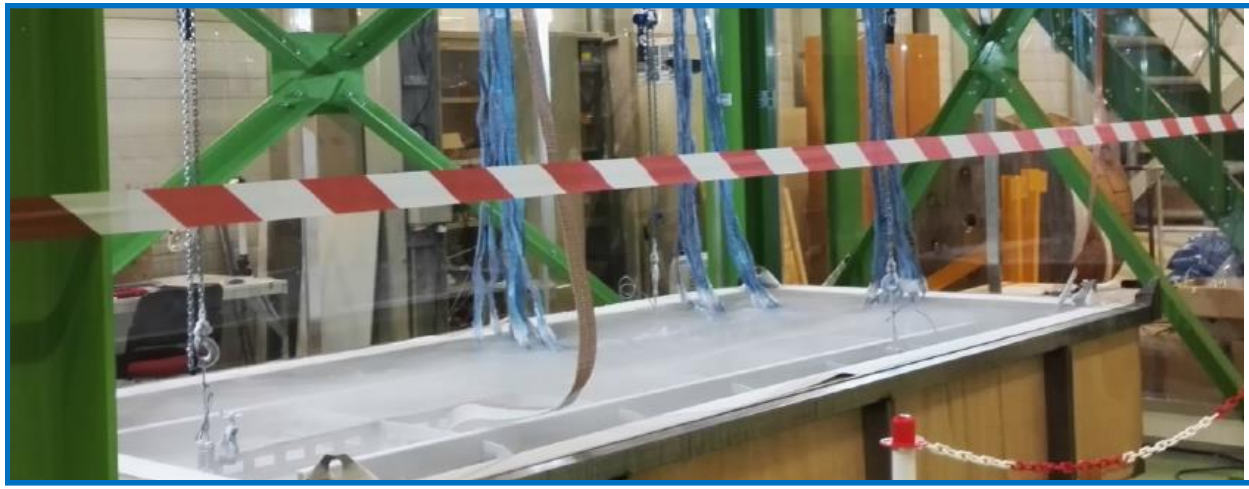
- Assembly straightforward (~2people, 2 days)

LEM + anode sandwich

50x50 cm2 PCB units

100micron diameter wires matching the 3mm readout pitch

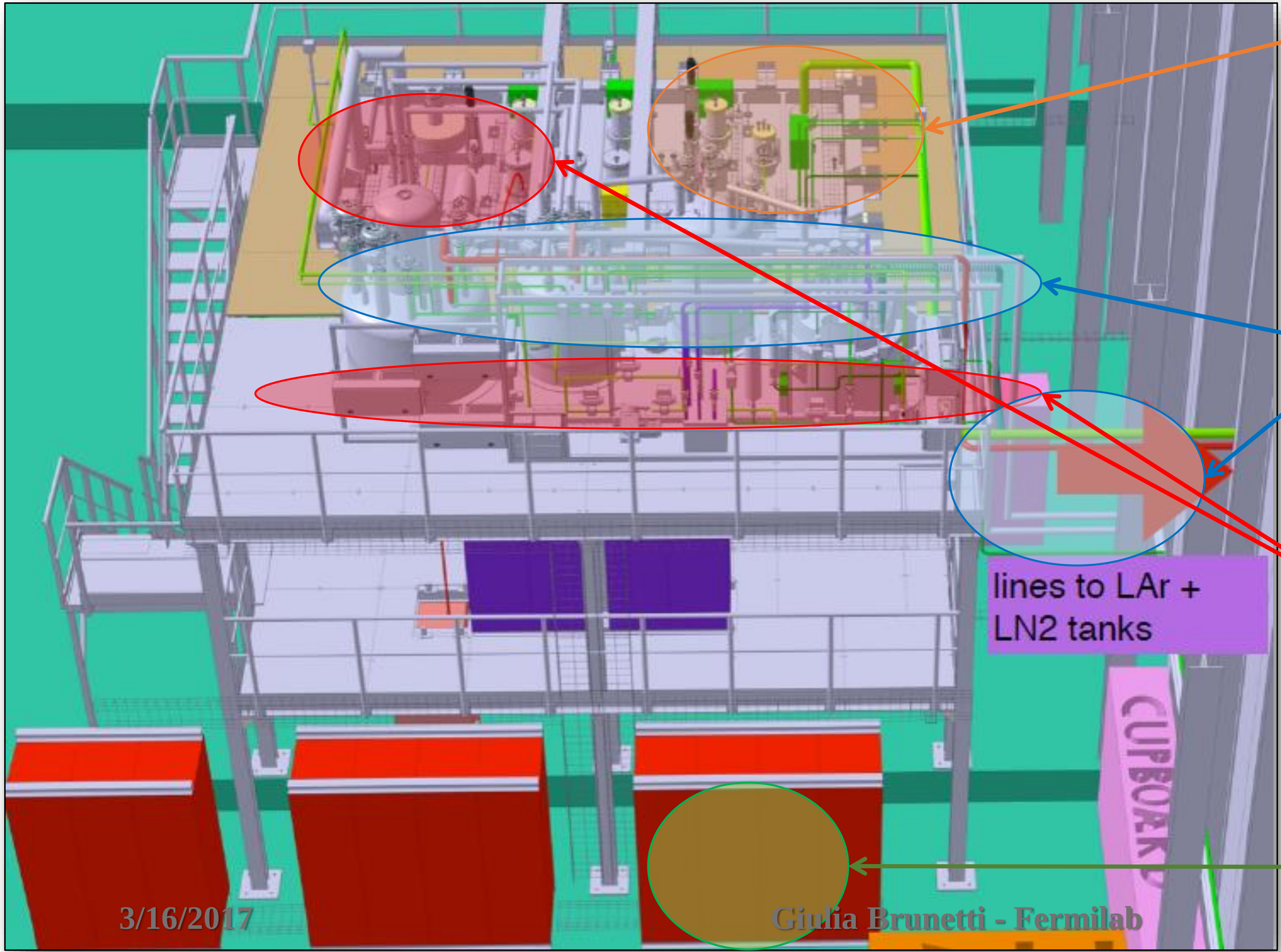
extraction grid



CRP suspended in bath for flatness measurement and contacts in cold
→ Check resistance to thermal shock and planarity at cold as well as signal continuity

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
Cryogenics

Installation of all components in ~4months



INTERFACES

- GAr piston purge, filling line (LAr+GAr), pump tower
- Mostly done before detector lifting (spring 2016)

COLD piping

- From August to October 2016 → ~4 weeks

WARM piping

- October & November → took more than expected

CONTROL

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 Feedthroughs

All the feedthroughs were tested over the past year. **Same ones to be installed in the protoDUNE-DP**

4 signal chimneys

3 slow control and medium voltage

3 CRP suspension

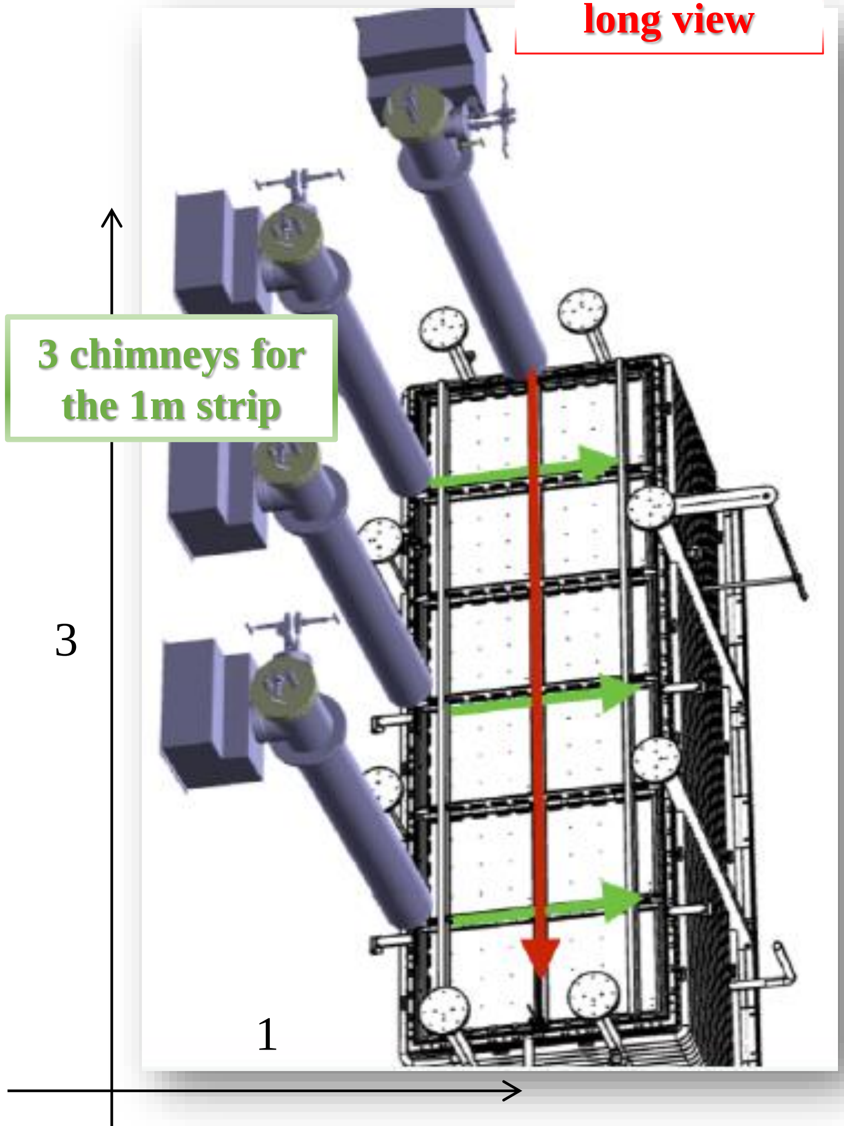
1 HV, operates at 50kV
(Tested at 300kV)

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 Signal Feedthrough

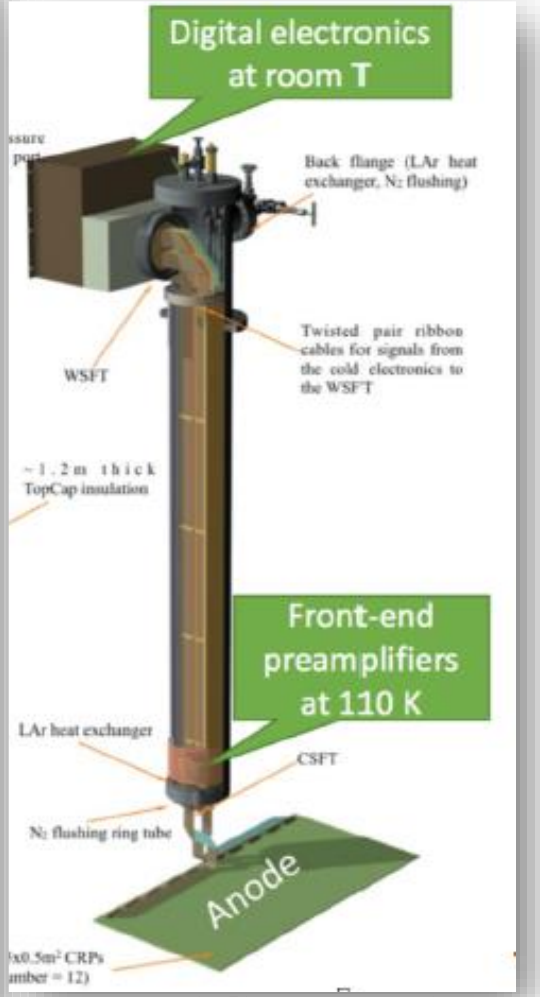
2-view readout

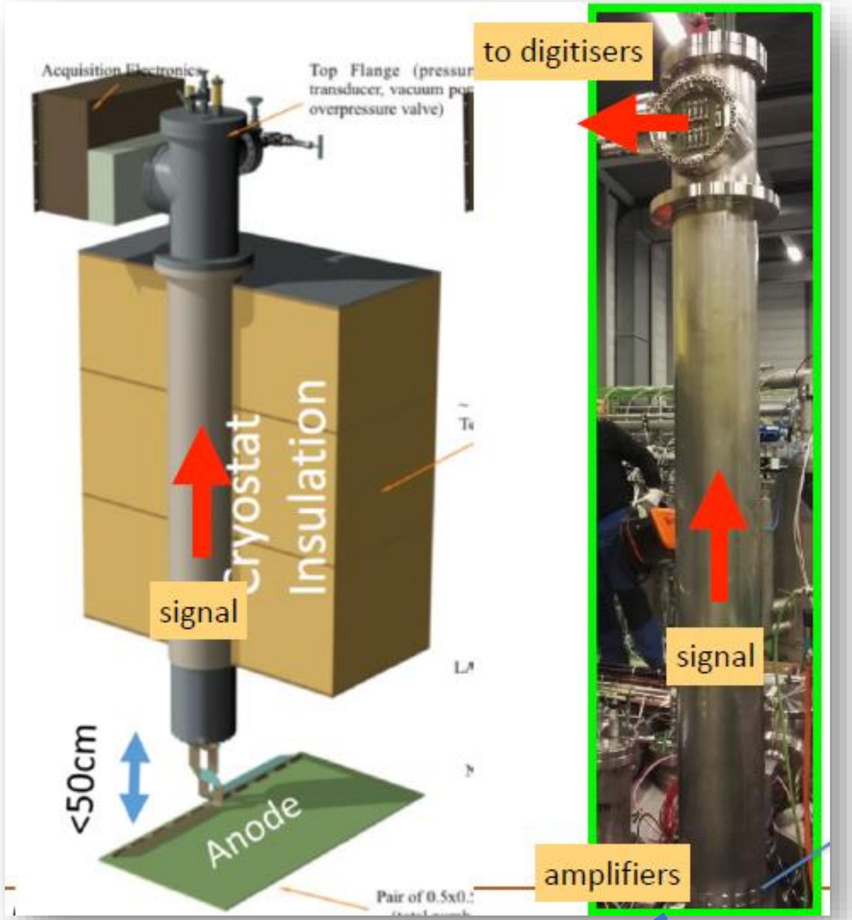
1 chimney for the 3m long view

3 chimneys for the 1m strip

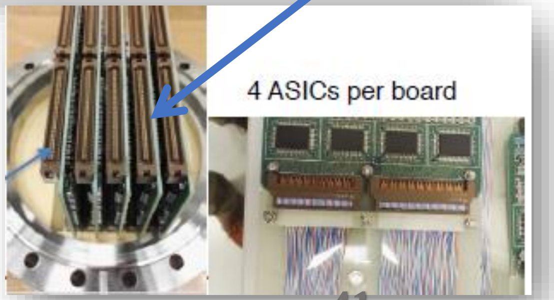


- Independent volumes to allow replacements of preamps
- Pumped to remove air and sealed





Amplifier
- **inside closed volume, closed to anodes, ~110K**
- **<u>Accessible during operations</u>**



THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
DAQ installation + measurements

- Several campaigns of measurements of the noise and grounding since June 2016
- Front-End: fully installed in September 2016
- μTCA racks and optical fibers cabling of data network and WR network: installed in October 2016
  → Another noise measurement campaign
    → Identification of main noise sources
- DAQ system installation completed in November/December 2016
  → Event Builder software debugging + Characterization and tests (no bad channels) of all the digitization cards

<u>Complete system fully commissioned at the beginning of December</u>: μTCA cards, GPS and WR system, event builder, run control, online data-storage and processing system, online event display

- Additional checks + some repairs done before closing the manhole mid-December
- Campaign of tests on noise from gas recirculation pump, HV LEM, HV cathode Level meters: January 2017

- **Beyond the 3x1x1, which produces a relatively small data flow, the whole farm system is a fundamental for a "mock data challenge" and various tests to study and optimize the design of the final high rate system for the 6x6x6**

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
FROM "CONSTRUCTION TO OPERATION"

- November/December 2016
  - Triggering scheme and cosmic ray trackers operational
  - Cryostat ready for purge
  - DAQ + pulsing system operational
  - Cross-check of all channels with DAQ
  - Sealing of manhole
  - Start of GAr piston purge

MONITORING

- >150 Temperature probes
- 20 pressure probes
- 30HV channels
- 1300 kV HV channels
- Gas+liquid purity monitors
- 15 level meters
- 5 cryo-cameras

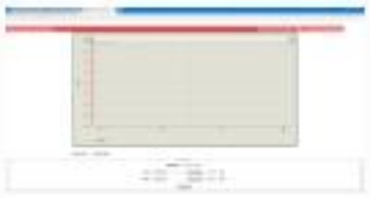
ALL ONLINE

Y.Rigaud, DUNE collab meeting, Jan 2017

- From 3m x 1m x 1m to protoDUNE-DP…
- Complete chain tested on 3m x 1m x 1m and totally functional
- Hardware design for protoDUNE-DP
- Software design for protoDUNE-DP

The complete chain has been tested and works very well on the **3x1x1**
→ Just need to transpose the solutions on **protoDUNE-DP** with some improvements

The 3m x 1m x 1m was an occasion to experiment sensors



SENSOR / ACTUATORS → ACQUISITION / CONTROL → SUPERVISION → DATABASE → WEBSITE

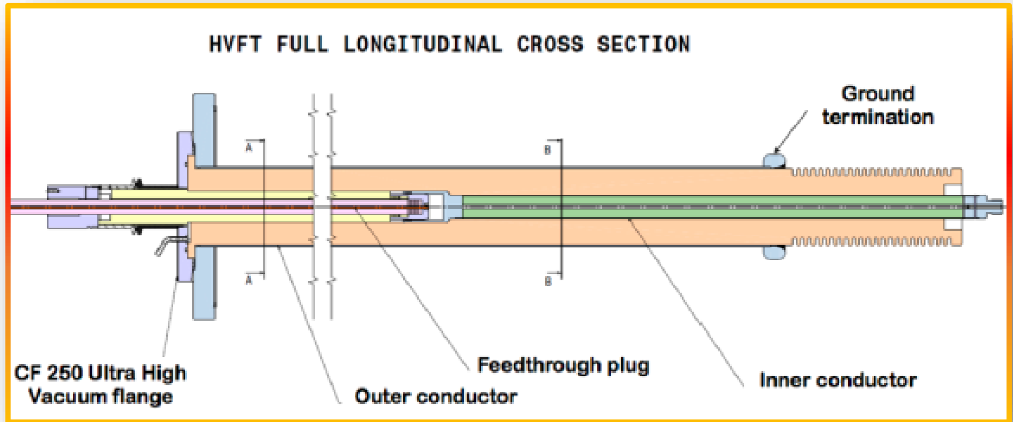
THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 FROM "CONSTRUCTION TO OPERATION"

High-Voltage

(arXiv:1611.02085v1)

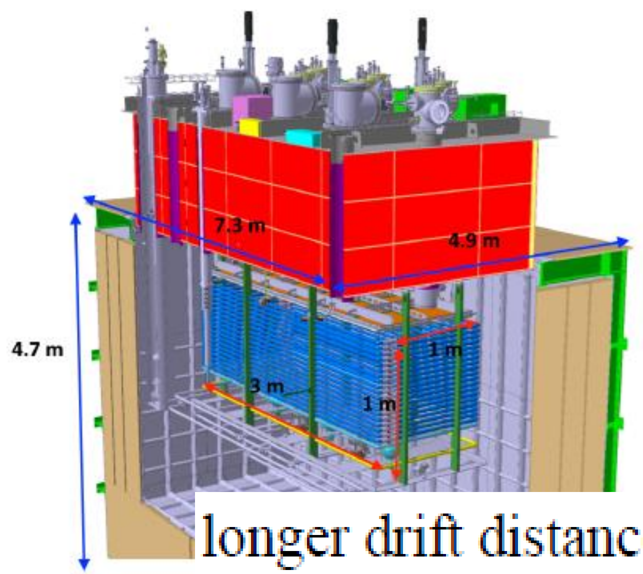
ABSTRACT: Voltages above a hundred kilo-volt will be required to generate the drift field of future very large liquid Argon Time Projection Chambers. The most delicate component is the feedthrough whose role is to safely deliver the very high voltage to the cathode through the thick insulating walls of the cryostat without compromising the purity of the argon inside. This requires a feedthrough that is typically meters long and carefully designed to be vacuum tight and have small heat input. Furthermore, all materials should be carefully chosen to allow operation in cryogenic conditions. In addition, electric fields in liquid argon should be kept below a threshold to reduce risks of discharges. The combination of all above requirements represents significant challenges from the design and manufacturing perspective. In this paper, we report on the successful operation of a feedthrough satisfying all the above requirements. The details of the feedthrough design and

High voltage feedthrough (HVFT)

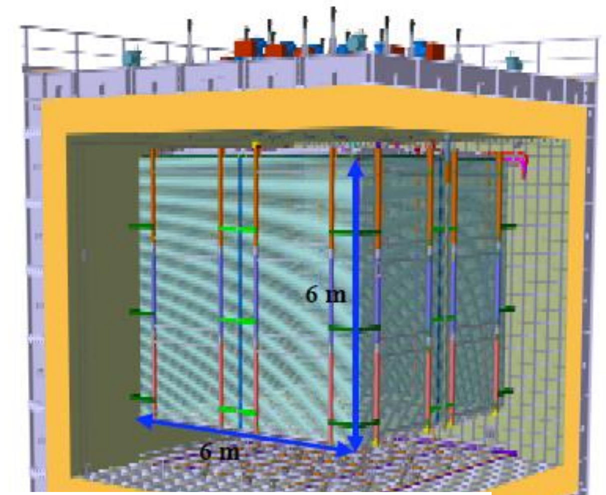


Very high voltages up to unprecedented voltages of -300 kV could be applied during long periods repeatedly.

3x1x1 prototype: 1m x 0.5kV/cm = 50 kV



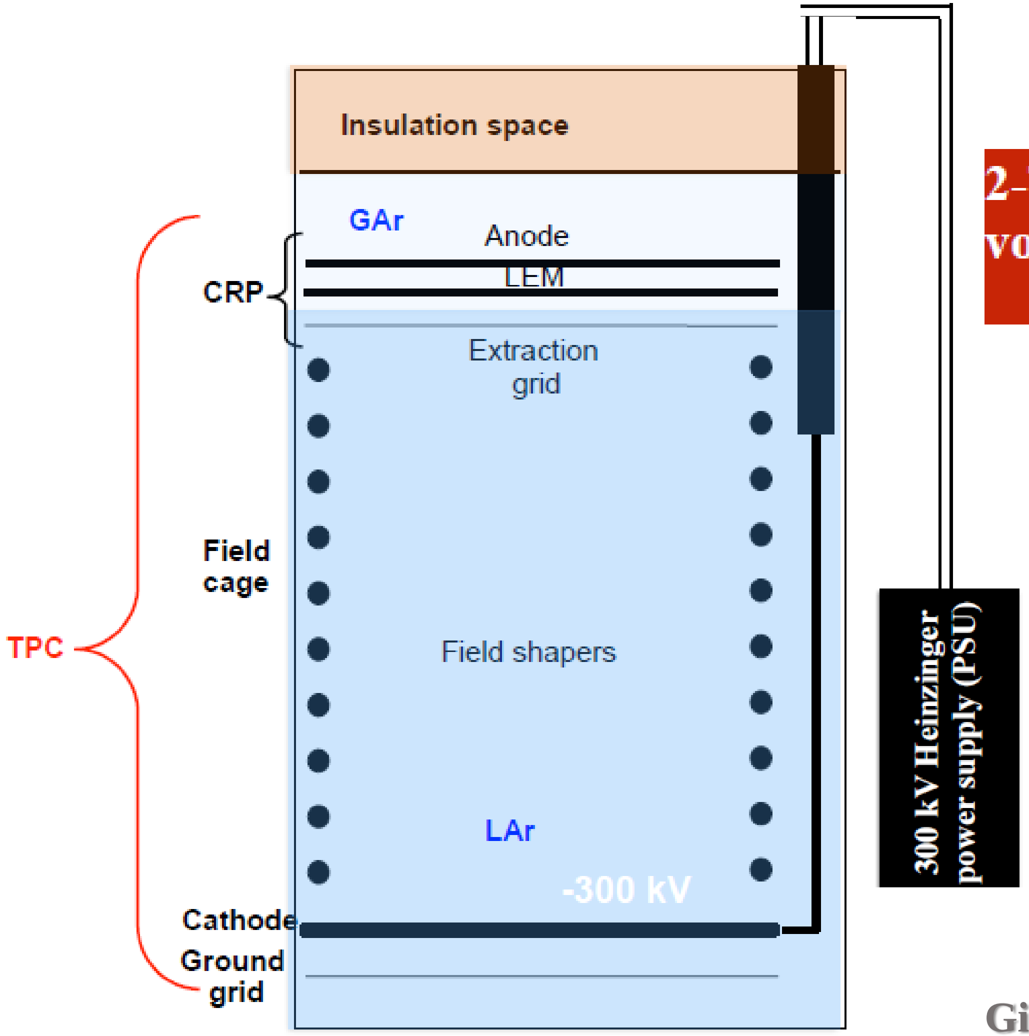
protoDUNE-DP: 6m x 0.5kV/cm = 300 kV



longer drift distances ➜ higher voltages

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 FROM "CONSTRUCTION TO OPERATION"

High-Voltage



2-Transmission of the nominal voltage from the power supply to the cathode

1-Generation of the nominal high voltage

High voltage feedthrough and electrostatic simulations for protoDune-DP

C. Cantini, P. Chiu, A. Gendotti, L. Molina Bueno, S.Murphy, A. Rubbia, C. Regenfus, F. Sergiampietri, S.Wu

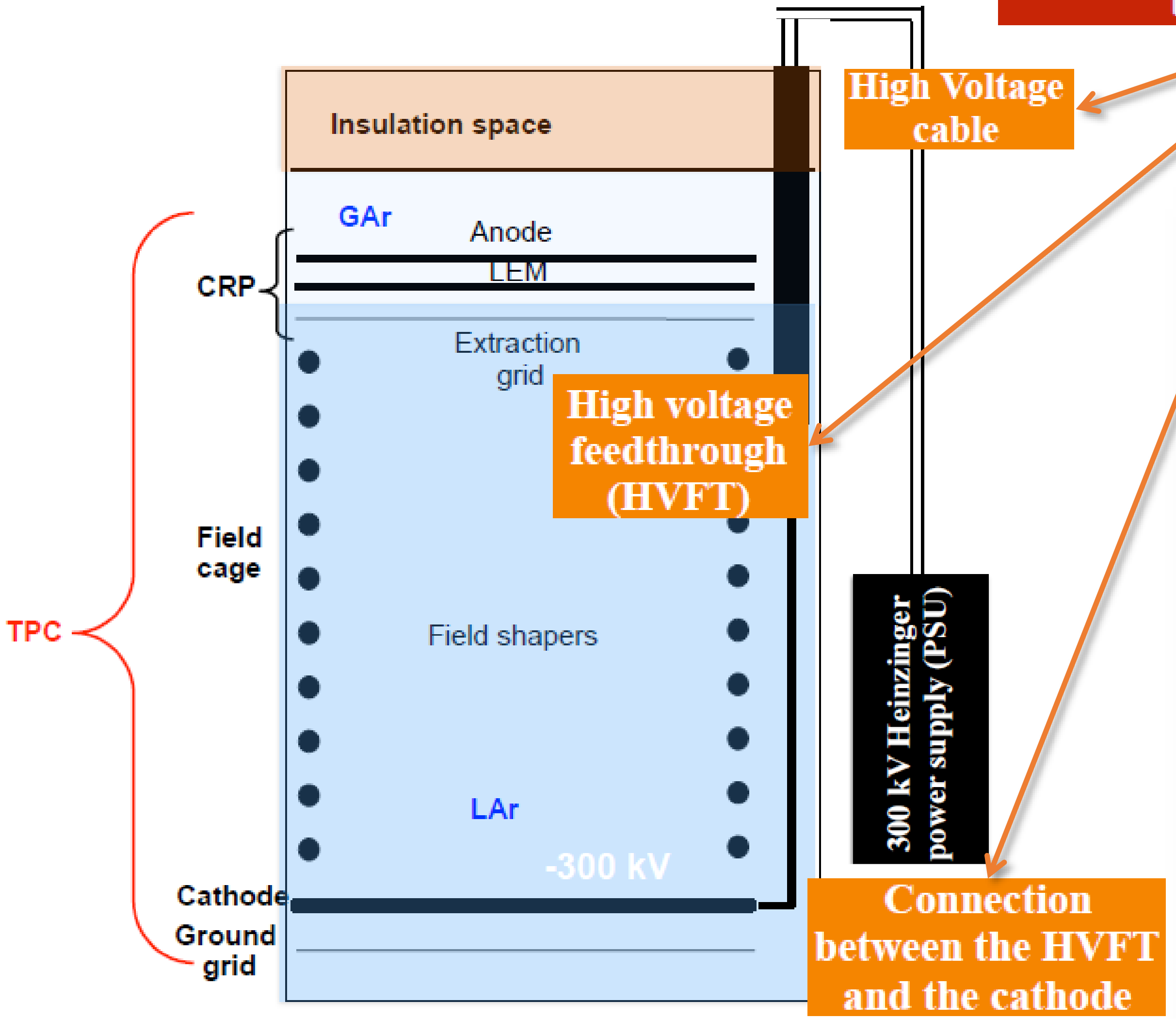
DUNE collaboration meeting, 23th-27th January 2017

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 FROM "CONSTRUCTION TO OPERATION"

High-Voltage

2-Transmission of the nominal voltage from the power supply to the cathode

"First Test of a high voltage feedthrough for liquid argon TPCs connected to a 300kV power supply"
arXiv:1611.02085v1

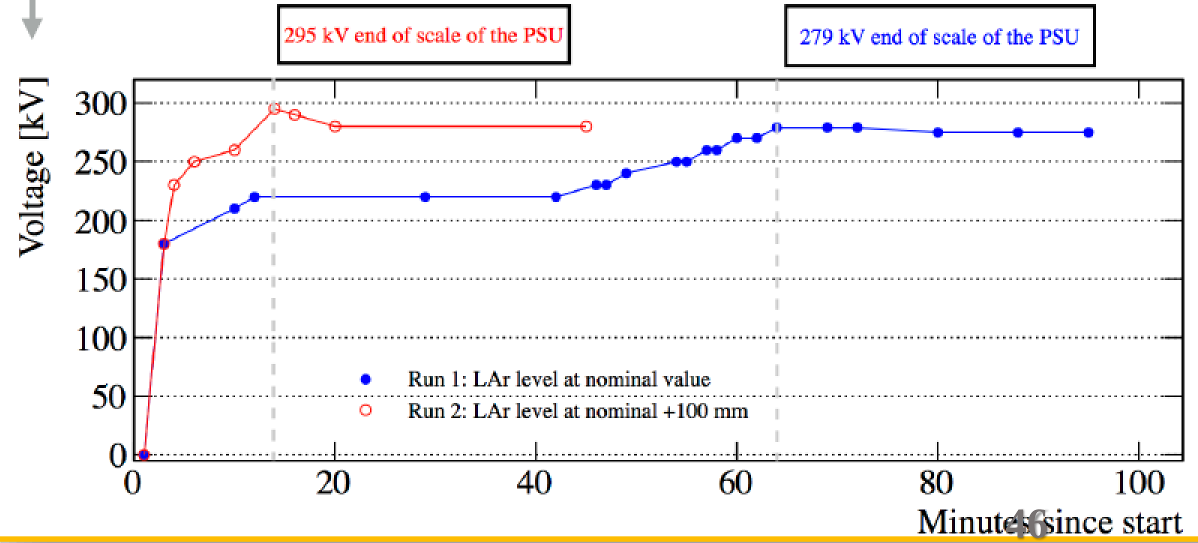


Two series of tests performed during September 2016

1-Ramping up the high voltage while monitoring the current and the voltage

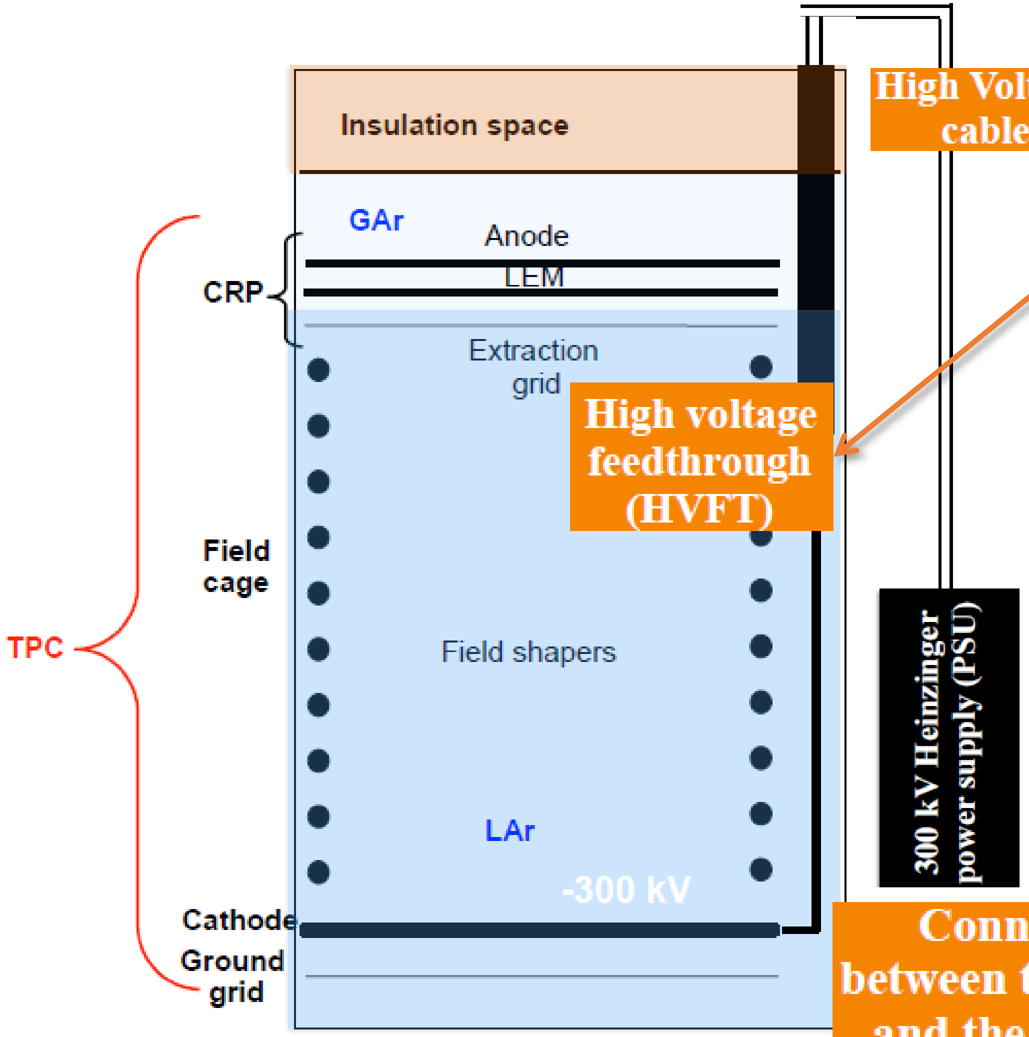
2-Test to undertand the stability of the feedthrough during long-term operations

Voltage [kV]	Pressure [bar]	O_2 impurities in gas [ppm]	Electric field at ground termination [kV/cm]
-275	1.02	< 0.1	80
-250	1.06	< 0.1	73
-100	1.06	< 0.1	29



THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
FROM "CONSTRUCTION TO OPERATION"

High-Voltage



2-Transmission of the nominal voltage from the power supply to the cathode

High Voltage cable

High voltage feedthrough (HVFT)

Connection between the HVFT and the cathode

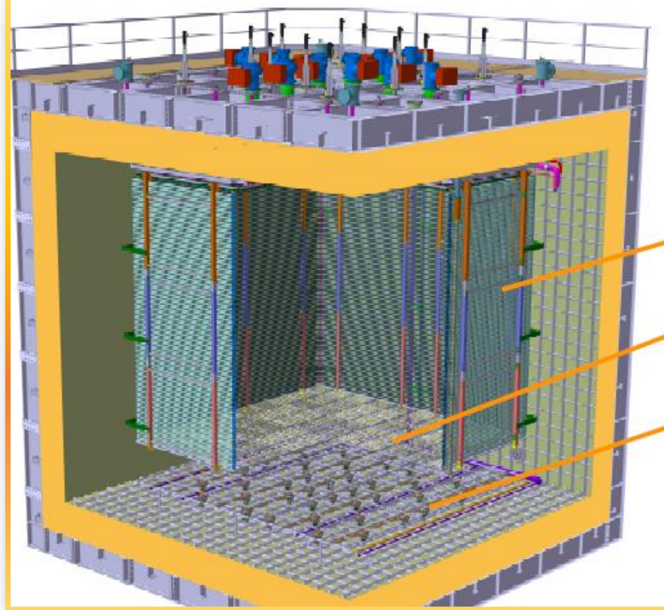
High voltage feedthrough and electrostatic simulations for protoDune-DP

C. Cantini, P. Chiu, A. Gendotti, L. Molina Bueno, S.Murphy, A. Rubbia, C. Regenfus, F. Sergiampietri, S.Wu

DUNE collaboration meeting, 23th-27th January 2017

The shape of the field cage and the cathode should be designed to avoid critical field regions (maximal electric field above 40 kV/cm)

3-ELECTROSTATIC SIMULATIONS



Electrostatic simulations of the different parts of the detector performed with COMSOL multi physics:

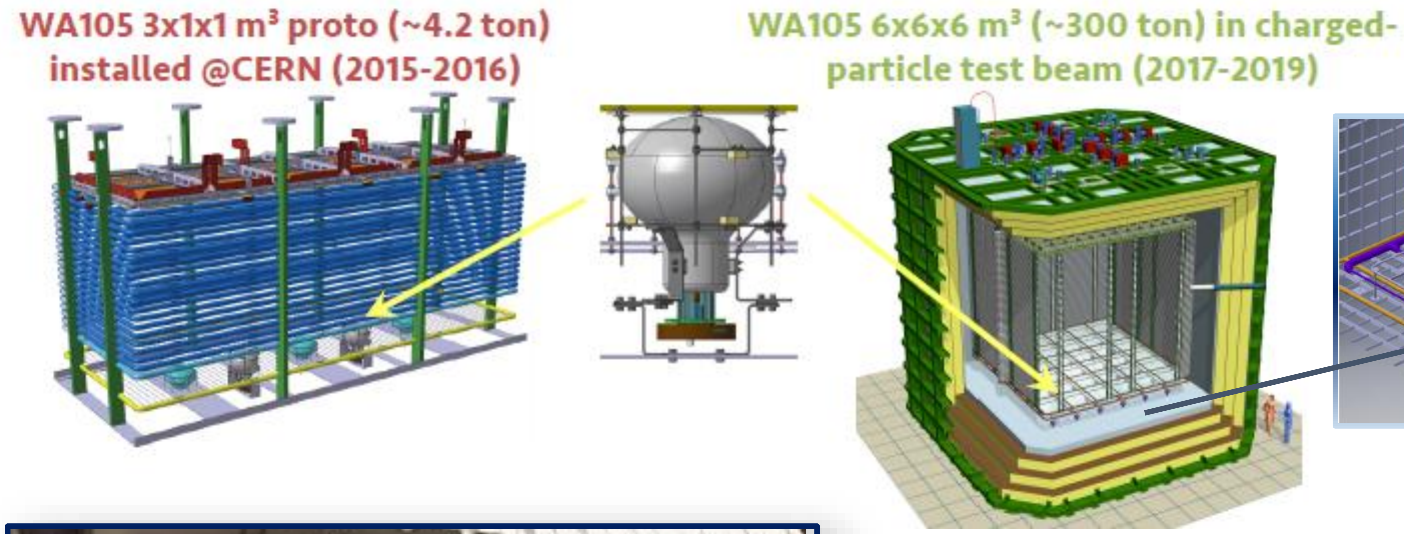
A. Field cage
B. Cathode
C. Ground Grid
D. HVFT

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 FROM "CONSTRUCTION TO OPERATION"

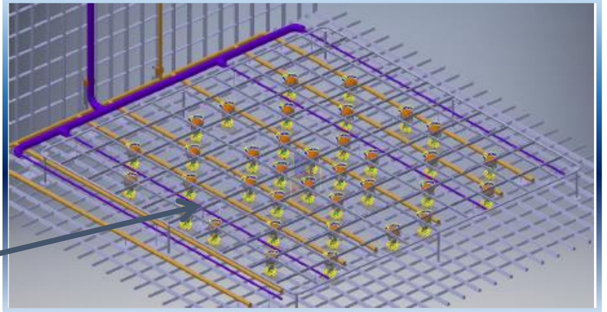
Light Detection System

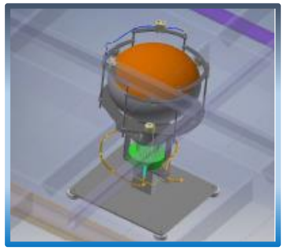
Inés Gil-Botella
DUNE Collaboration meeting, Jan 2017

From 3x1x1 m^3 ⇨ 6x6x6 m^3



40 PMTS. the PMT will be placed at the center of the membrane corrugation squares

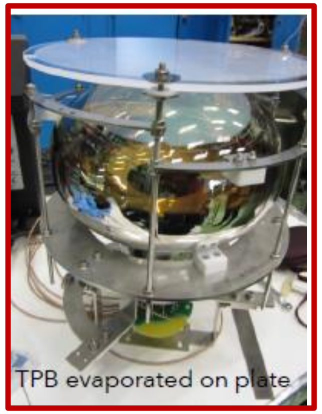




Several options studied to avoid interferences with the piping system

- One of the goals of the 3x1x1 m^3 prototype is to test different configurations of the systems in real conditions
- In order to take a decision on the optimal configuration for the 6x6x6 m^3 light detector system, we need input from the 3x1x1 m^3 light data
- Different options are being tested

Wavelength shifters options

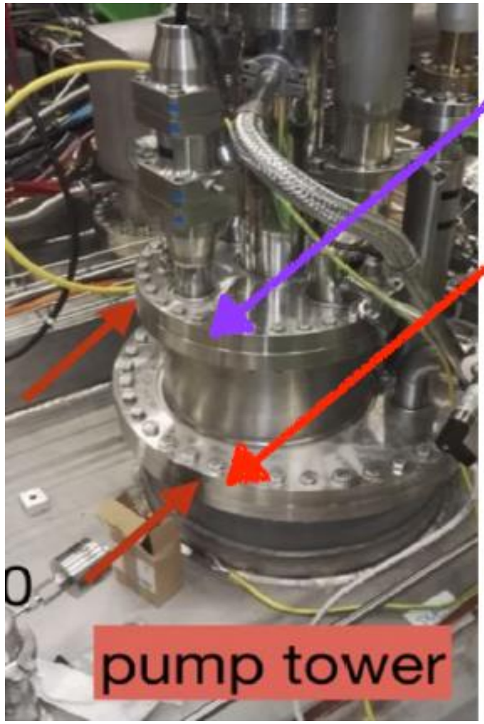


THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
FROM "CONSTRUCTION TO OPERATION" – December 2016 Ready for purge

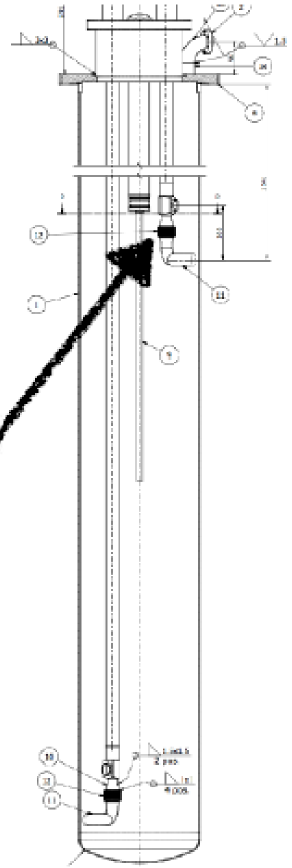
1. Remove the contaminants by flushing gas argon and recirculating and filtering in closed loop
2. Observe purity evolution with 3 gas trace analyzers: Nitrogen, Oxygen, water (all 100 ppb precision) all pre-tested and operated beforehand

- On December 19th 2016 the Manhole was sealed and GAr was flushed to pressurize the tank…

→ Leaks were found on both flanges of the pump tower, coming from 3 independent problems



- the CF-250, rotatable flange too deep badly manufactured.
- the CF-400, gasket was not properly fixed because the flange was deformed during welding (not perfectly flat and round)
- the leaks from pump tower to main volume. Cause broken below. More problematic had to be brought to main workshop for replacing and reinforcing below.



1. No incision on the copper gasket, gasket was at the same high of the flange → **problem solved by putting a spacer underneath**
2. **Solved by carefully screwing and positioning the gasket**
3. Inspection with and endoscope, broken bellow, probably damaged during transport → **pump tower dismantled and sent to workshop for repairing and reinforcing**

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
The membrane cryostat + Insulation

INSULATION

- 1 meter made from blocks of 30 cm thick polyurethane+plywood
- 45 temperature sensors → measure T gradient

MEMBRANE

- Corrugated steel panels welded together
- Tightness of welds tested to 1e-9 mbar l/s

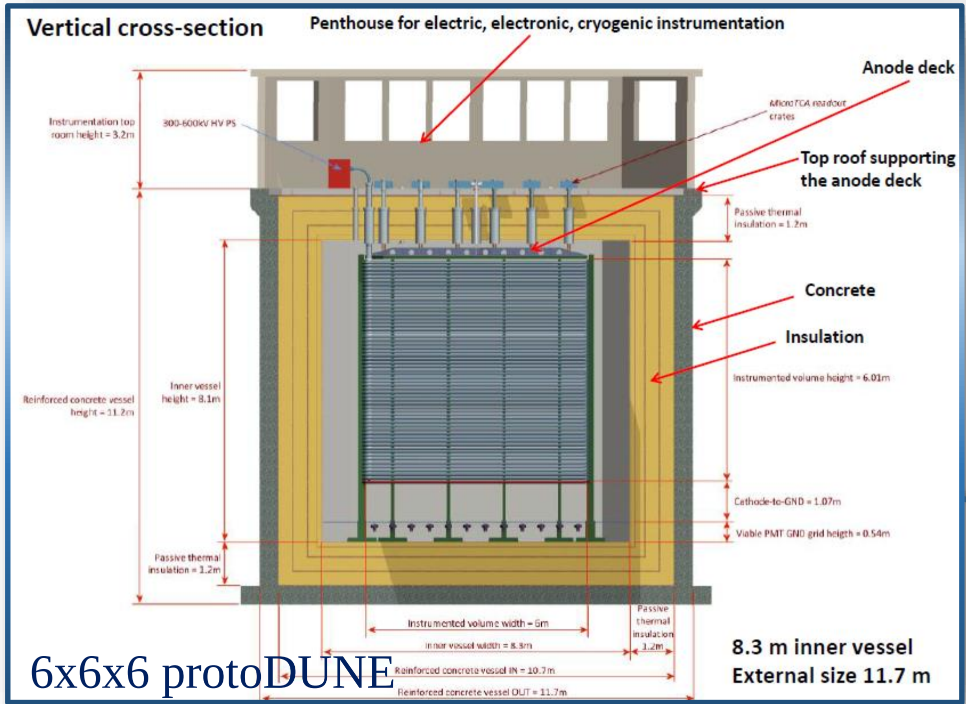
THE DUAL-PHASE “proto” protoDUNE – The 3x1x1
The membrane cryostat + Insulation

- During cooling down in March 2017: a layer of frost developing on the bottom south east corner of the 3x1x1 cryostat was observed on an area of approximately 50x50 cm2
- The tank was in slow cool down phase (few kelvin/hour) with a minimum measured gas temperature of 176K
- No liquid argon was introduced.
- Multiple checks and discussion with GTT experts

  → **Leak from the inner membrane to the insulation space**

  → start warming up the tank in view of an inspection by CERN and GTT

Infrared pictures → cold spot of down to -40C on the outer structure at specific corner

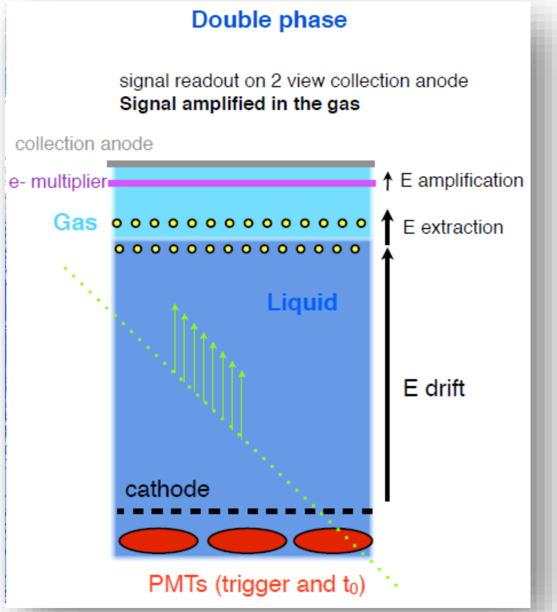


6x6x6 protoDUNE

- Delay on the commissioning likely of several weeks.
- Membrane break was indicated as highly improbable (almost impossible) by GTT
- ***General problem for the DUNE program as this membrane is the first prototype for all the DUNE cryostats*** (both proto detectors + DUNE FD) → Very important to understand the problem

Conclusions

- **The dual-phase design provides many appealing aspects**
  - Fully active volume without dead material
  - Anode with 2 collection (X, Y) views (no induction views), no ambiguities
  - **Tunable gain in gas phase (20-100), high S/N ratio for m.i.p.**
  - Accessible and replaceable cryogenic FE electronics, smaller nb of readout channels, finer readout pitch
- **Already many small dual-phase detectors successfully operated, result of many years of R&D**
- The Goal: **Dual-phase 10 kton FD for DUNE**



The road to the DualPhase FD:

- **Long standing efforts during the last 10 years → now large scale implementation with the 6x6x6 detector operation in the CERN North Area – The protoDUNE Dual-Phase prototype**
  → detector exploitation in 2018 with the collection of about 100M of beam triggers

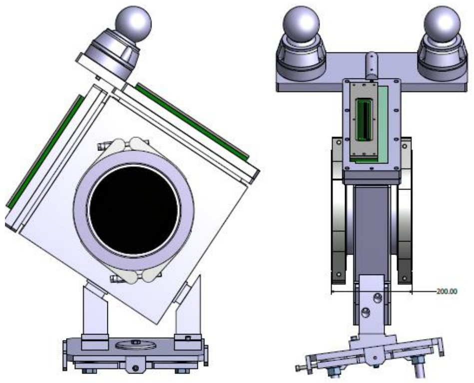
- **The activity on the 3x1x1 pilot detector has been extremely useful in order to reach an advanced state of prototyping (and costs assessment) of most of the components for the 6x6x6.**
  The assembly was completed in the Fall 2016 and its cryogenic system in December.
  Most of what has been presented on the 3x1x1 pilot detector has been designed to match the scale of protoDUNE
  → installation and commissioning steps provided many valuable inputs and highlighted various problems
  → lessons learned in view of the 6x6x6

Back ups

Momentum [GeV/c]	anti-p	e-	e+	K-	K+	mu-	mu+	p	pi-	pi+
0.4	0.00%	0.00%	97.61%	0.00%	0.00%	0.00%	0.00%	0.48%	0.00%	1.91%
1	0.00%	0.00%	74.20%	0.00%	0.00%	0.00%	0.00%	14.94%	0.00%	10.86%
2	0.00%	0.00%	45.83%	0.00%	0.67%	0.00%	0.96%	20.04%	0.00%	32.50%
3	0.00%	0.00%	68.29%	0.00%	0.64%	0.00%	0.42%	7.72%	0.00%	22.94%
4	0.00%	0.00%	53.72%	0.00%	1.46%	0.00%	0.65%	7.56%	0.00%	36.61%
5	0.00%	0.00%	42.38%	0.00%	2.47%	0.00%	0.83%	9.18%	0.00%	45.14%
6	0.00%	0.00%	31.42%	0.00%	3.83%	0.00%	0.73%	10.10%	0.00%	53.92%
7	0.00%	0.00%	24.70%	0.00%	4.08%	0.00%	0.85%	9.92%	0.00%	60.46%
8	0.00%	0.00%	19.36%	0.00%	5.11%	0.00%	0.97%	11.33%	0.00%	63.24%
9	0.00%	0.00%	15.12%	0.00%	5.67%	0.00%	0.82%	11.10%	0.00%	67.29%
10	0.00%	0.00%	12.36%	0.00%	6.02%	0.00%	0.71%	12.25%	0.00%	68.66%
11	0.00%	0.00%	10.46%	0.00%	6.95%	0.00%	0.82%	13.57%	0.00%	68.20%
12	0.00%	0.00%	8.90%	0.00%	6.89%	0.00%	0.66%	14.26%	0.00%	69.30%

Tertiary Beam composition for secondary beam +80 GeV/c

protoDUNE-DP Beam



BPROF's 1 mm fibers pitch
2 mm thick scintillator tiles

Final PID scheme:

- TOF with BPROF's – distance ~32 m
- 1 "low pressure" XCET - < 3bar pressure ("C1")
- 1 "high pressure" XCET - ≥ 15 bar pressure ("C2")

Momentum (GeV/c) / Particle	e	π	K	p
0.4 - 3.0	*C1 CO2 @ 1bar*	TOF	0	TOF
3.0 - 5	C1 CO2 @ 1bar	C2 CO2 @ 3.5 bar	No C2	No C2
5.0 - 12.0		C1 CO2 @ 1bar	C2 CO2 @ <= 14bar	No C1 No C2

Baseline : No K/p separation between 3 - 5 GeV
No e- tagging in the 'high energy' regime 5-12 GeV

Plans for ProtoDUNE dual-phase
Dario Autiero, DUNE Collaboration Meeting, January 2017

Beam time requests

- Maximum particle rate to avoid too many particle overlaps in TPC:

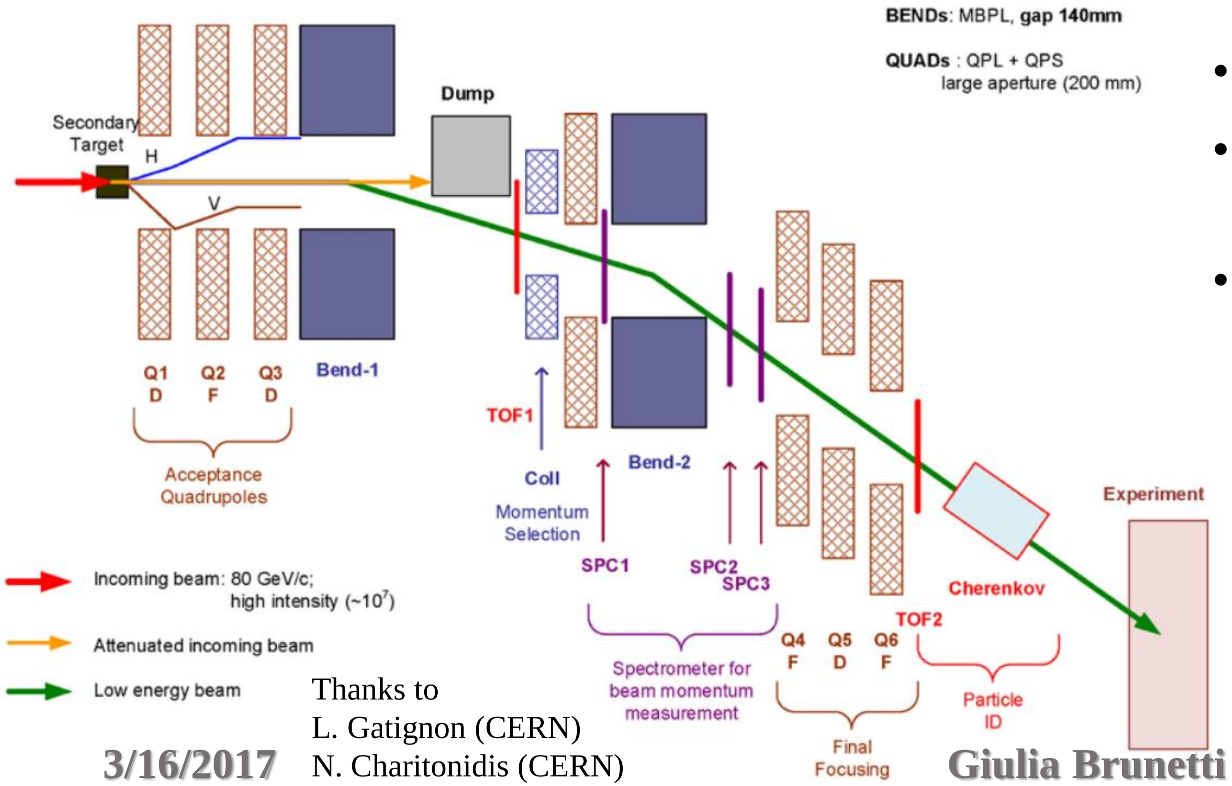
$$R = 100 \text{ Hz}$$

Assume this could be achieved for any momentum setting of the beamline

- For SPS spill of *4.8 s* and super-cycle of *2 spills / 50 s* the number of particles expected to be delivered to the detector per super-cycle

$$2 \times 4.8\ s \times 100\ Hz = \sim 1000 \text{ particles / super-cycle}$$

- Assuming 50% running efficiency: **~829k per day**



- Simulation of beam developed with G4Beamline toolkit
- Detailed breakdown of particles rates obtained for different species to estimate required running time
- →about 100M beam triggers expected on 120 days

Thanks to
L. Gatignon (CERN)
N. Charitonidis (CERN)

Beam time requests

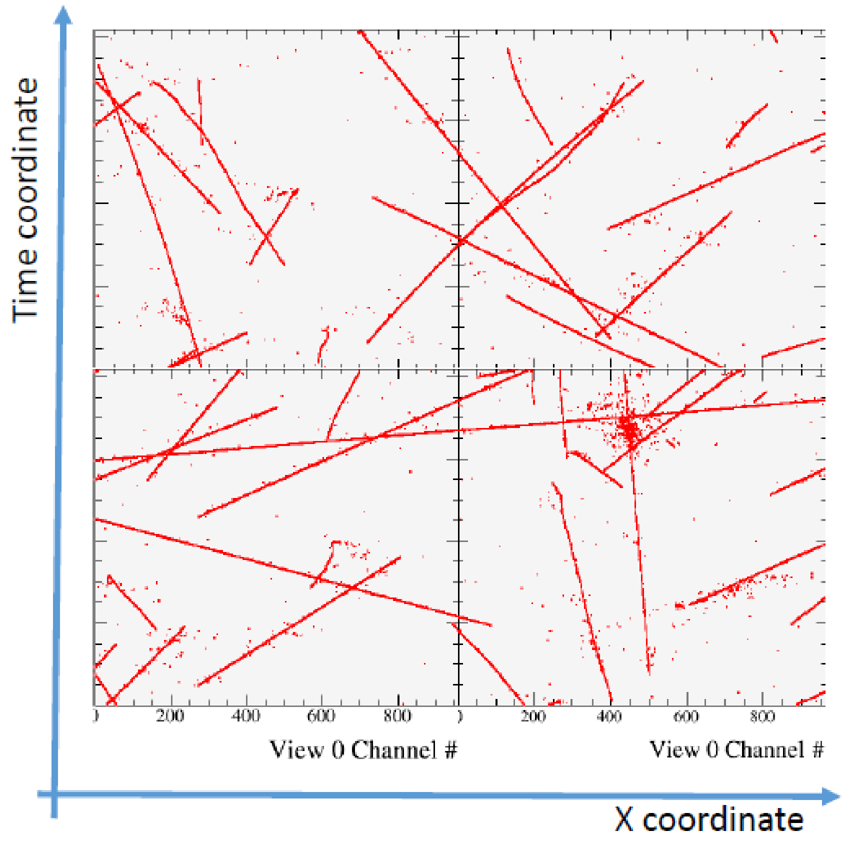
Momentum GeV/c	Surviving π's	Surviving K's	Beam composition $\pi/K/e/p$	π's Stat. (10^6)	Days for π's Stat.	Others $p/K/e$
Positive						
0.4	21%	0.05%	1%/-/22%/13%			
1.0	52%	1%	4%/-/85%/4%	0.5	14	$500k/-/9.8M$
2.0	72%	9%	18%/1e-4(CMS)/68%/7%	1	7	$405k/-/3.8M$
3.0	80%	20%	29%/1e-3(CMS)/56%/7%	2	8	$480k/-/3.8M$
4.0	85%	30%	39%/2%/45%/7%	2	6	$355k/106k/2.3M$
5.0	88%	38%	55%/2%/26%/8%	2	4	$307k/84k/934k$
6.0	90%	44%	56%/4%/21%/10%	1.5	3	$259k/114k/554k$
7.0	91%	50%	67%/6%/10%/10%	1.5	3	$211k/127k/230k$
8.0	92%	54%	61%/6%/13%/11%	1.5	3	$281k/148k/327k$
9.0	93%	58%	67%/6%/10%/10%	1.5	3	$211k/127k/230k$
10.0	94%	61%	69%/6%/10%/9%	1.5	3	$202k/136k/215k$
11.0	94%	64%	70%/6%/7%/10%	1.5	3	$204k/136k/144k$
12.0	95%	67%	68%/8%/5%/14%	1.5	3	$301k/183k/111k$
					~ 59 days	
Negative					~ 59 days	

The running time in each momentum set is calculated based on the number of days needed to collect a desired pion statistics with reasonable rates for other particles acquired in “parasitic” mode taken into account

Typical event signature for ground surface Liquid Ar TPC operation

For each beam trigger we can have on average 70 cosmics overlapped on the drift window after the trigger (these cosmics may have interacted with the detector in the 4 ms before the trigger and in the 4 ms after the trigger → chopped tracks, "belt conveyor" effect

In-spill cosmics in charge data

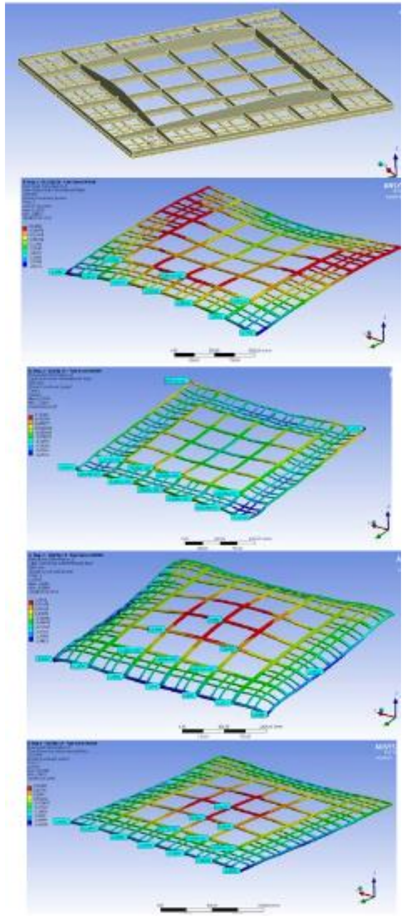


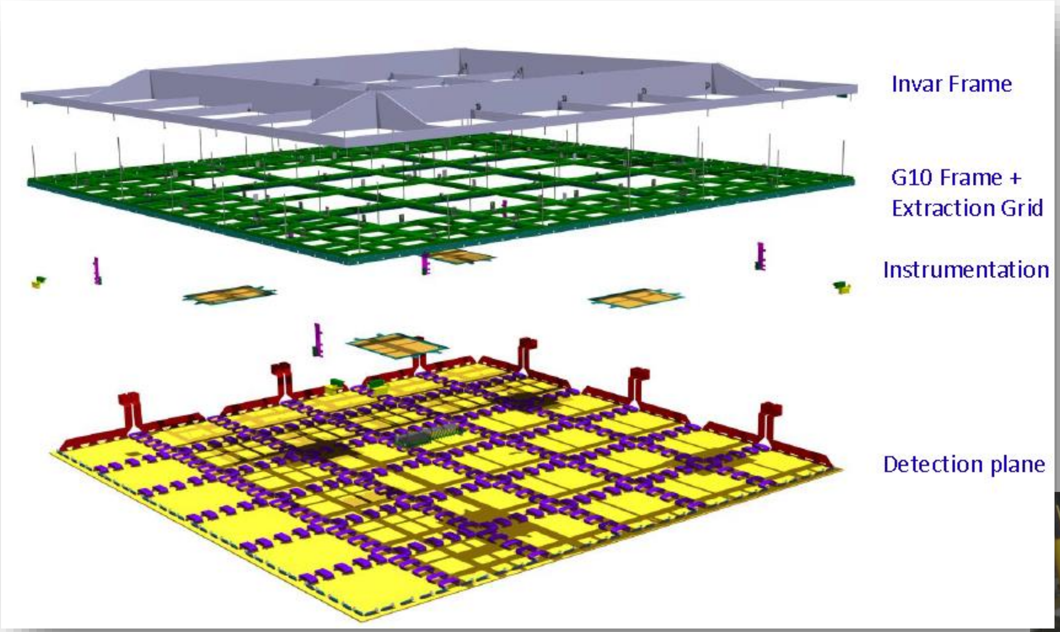
Example of cosmics only event (in one of the views)

- Red points are reconstructed hits
- TPC is readout in 4 3x3m^2 modules
- After track reconstruction:
  - Attempt to correlate found tracks with light data
  - Remove CR background from beam event
  - Select a subsample of long tracks for calibration purposes

8

→ **Invar frame + decoupling mechanisms in assembly in order to ensure planarity conditions +-0.5 mm (gravity, temperature gradient) over the 3x3 m^2 surface which incorporates composite materials and ensure minimal dead space in between CRPs**





B. Aimard (CRPs) and A. Delbart (LEM-anodes production) DUNE Collab Meeting Jan 2017

protoDUNE – DP

3x3 m^2 CRPs integrating the LEM-anode sandwiches (50x50 cm^2) and their suspension feedthroughs

CRP mechanical structure design:

→ **campaign of cold bath tests + photogrammetry on differential effects in thermal contraction, design of decoupling mechanism**

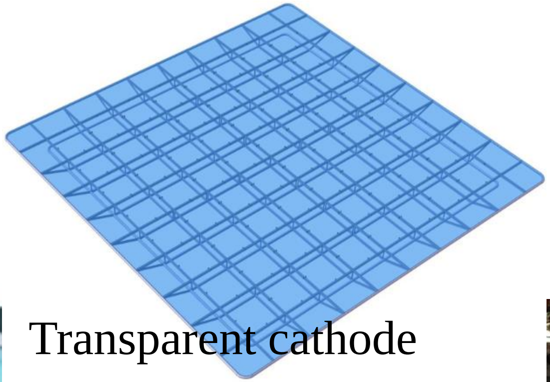
Plans for ProtoDUNE dual-phase
Dario Autiero, DUNE Collaboration Meeting, January 2017

Cathode

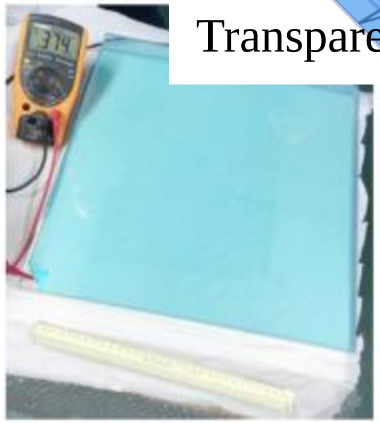
Transparent cathode with ITO (Indium-Tin-Oxyde) **resistive coating** on two sides of PMMA plates + TPB deposition at the top side:

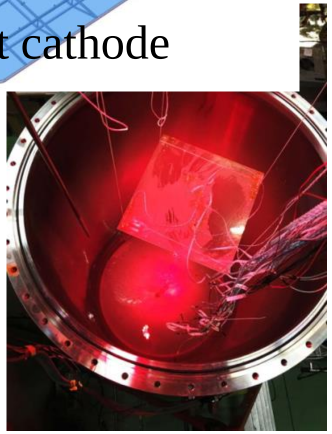
- R&D and conceptual design for plates integration in cathode structure completed
- Infrastructure set up for TPB evaporation coating
- Tested ITO coated PMMA plates up to 850x600 mm^2

(produced by industry) → chosen size 650x650x10 mm^3



Transparent cathode



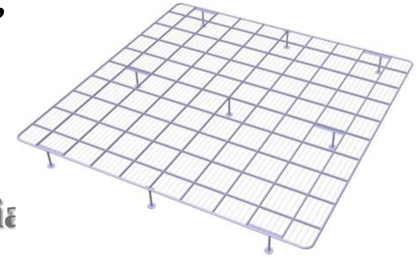


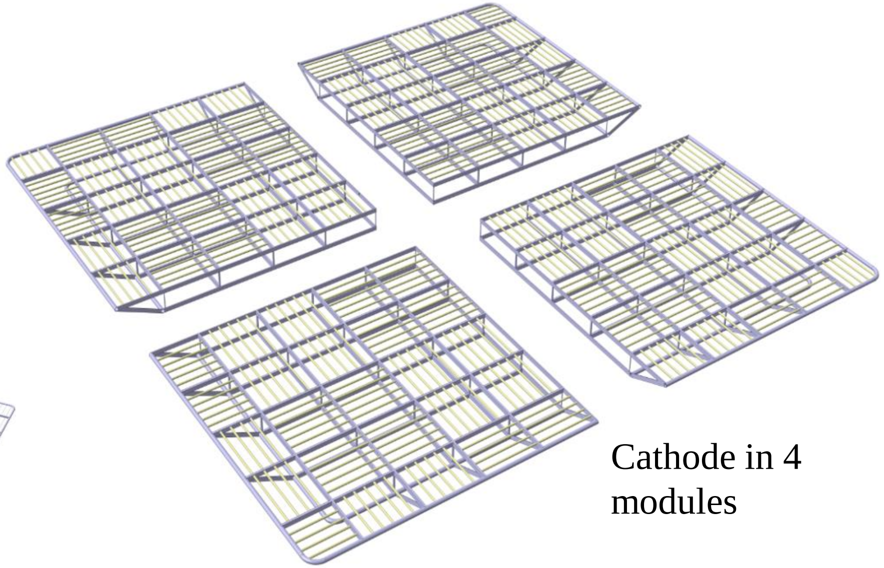
LBNC meeting of October 2016: PMMA cathode, despite all successful R&D, introduces many elements of novelty in the 6x6x6 design and possibly some risks which will not be retired by the 3x1x1 operation

→ **decided to reactivate the baseline design of the cathode, based on a mesh of pipes (extensively studied in the LAGUNA-LBNO DS and WA105 TDR)**

→ **Minimal changes to the structure made for PMMA inserting 20 mm SS pipes with 105 cm pitch, completion of executive design, full simulations showing E<30 kV/cm**

Ground grid above the PMTs, 2mm wires embedded in a SS frame 40/20 mm pipes, assembled in 4 modules



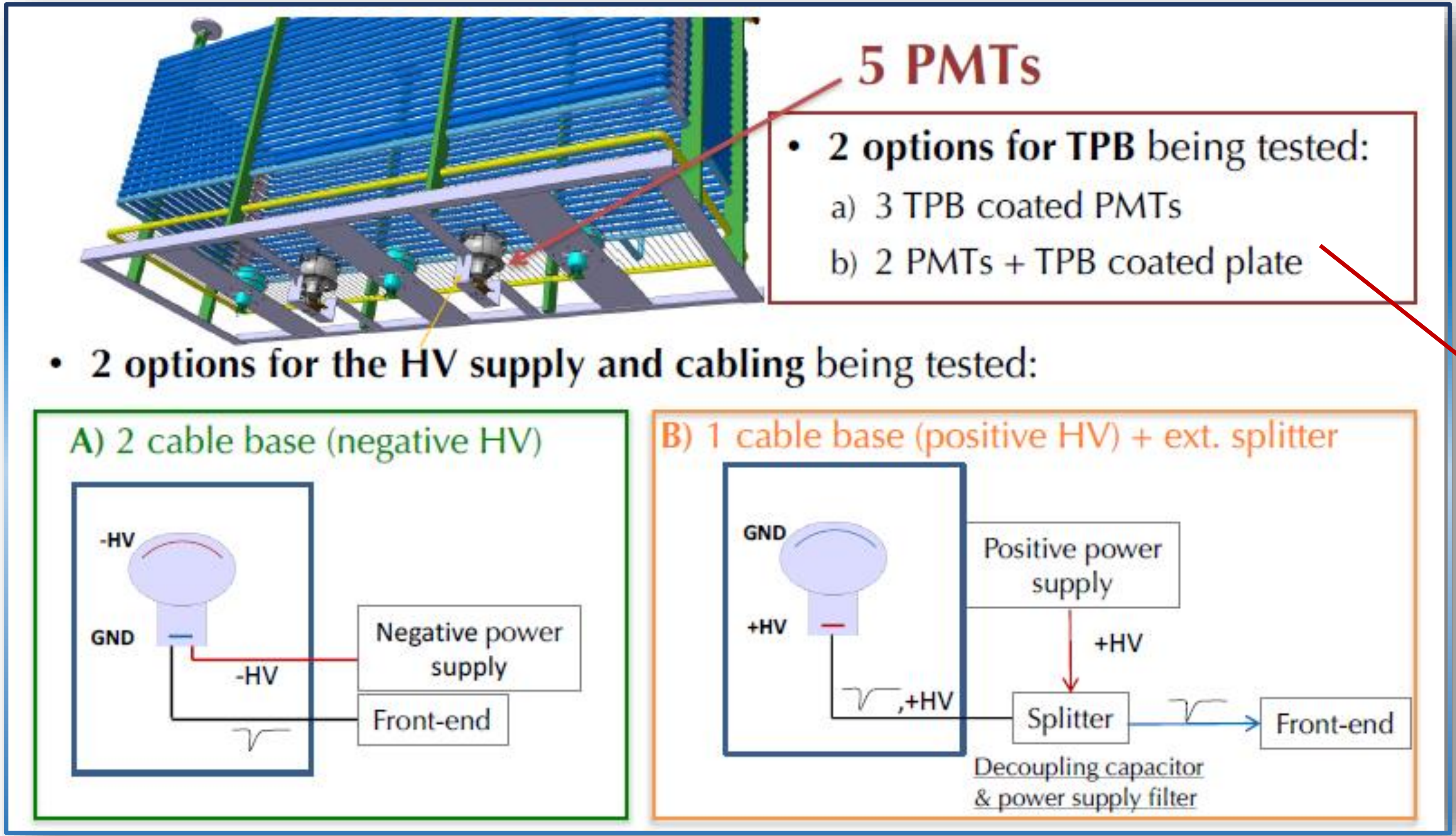


Cathode in 4 modules

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 FROM "CONSTRUCTION TO OPERATION"

Light Detection System

Inés Gil-Botella
DUNE Collaboration meeting, Jan 2017

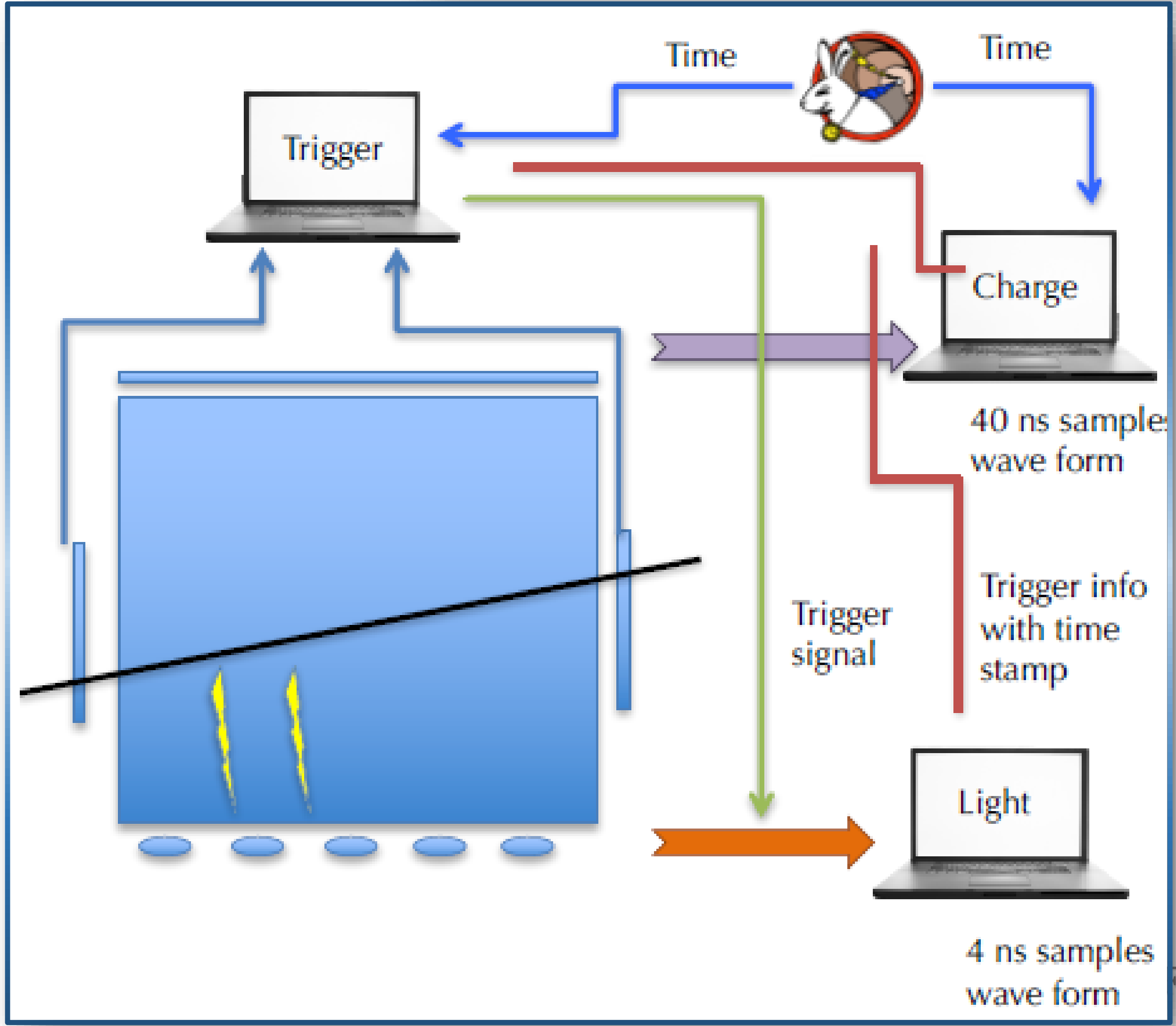


Wavelength shifters options

Light Detection System

Inés Gil-Botella
DUNE Collaboration meeting, Jan 2017

Foreseen light tests with the 3x1x1



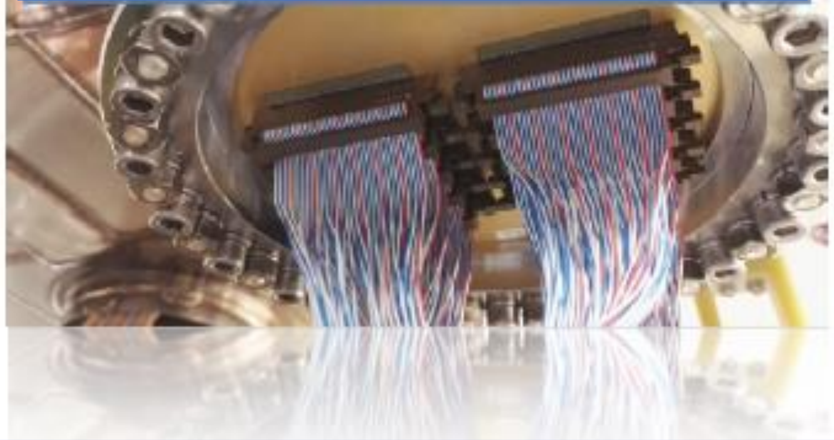
- Simple light **DAQ** installed
- **Goals**: understanding the light levels at surface under different operation conditions, S1/S2, cosmic background, performance with different light detection components
- **Measurements:**
  1. Commissioning: PMT HV scan, drift field scan and LEM HV scan
  2. PMT response stability
  3. Study of light signals in coincidence with cosmic muons
  4. Study of light and charge coincident signals

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 Charge Readout

INSIDE the detector – Not accessible

1. Charge signal multiplied and collected on low capacitance anode strips

2. signal guided to cold amplifiers by group of 32 channels



SIGNAL Feedthrough - Accessible

3. Signal amplified in cold

4. Signal brought outside by vacuum tight custom design PCB FLANGES

5. Signal digitized in uTCA crates

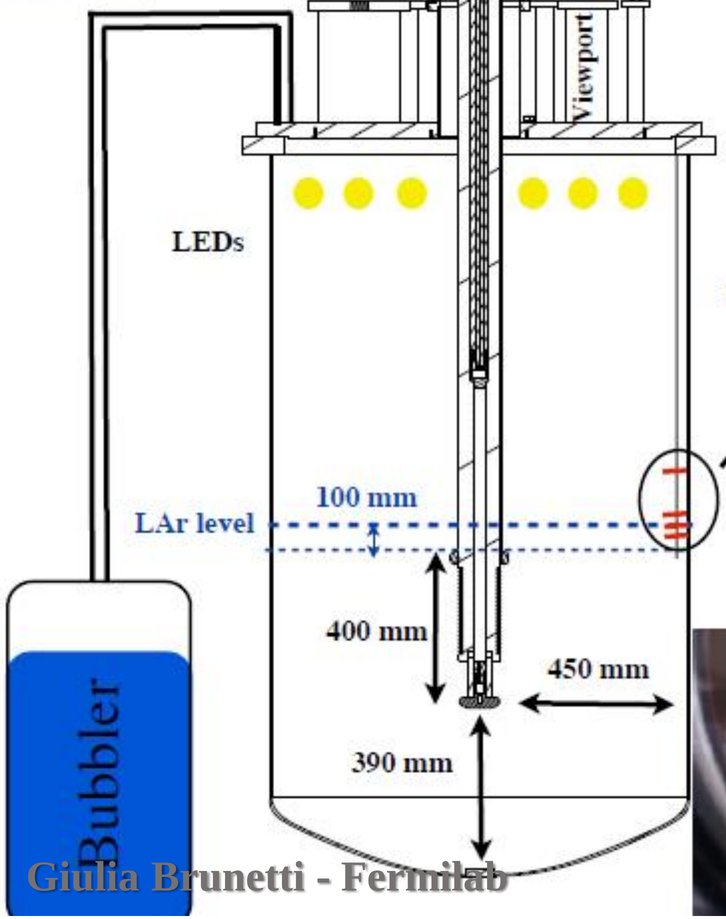
THE DUAL-PHASE "proto" protoDUNE – The 3x1x1

High-Voltage

HV cable

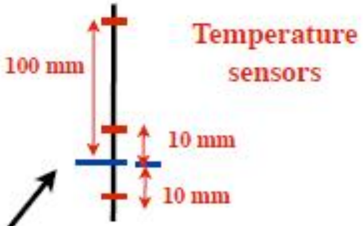
1:1 transformer

HVFT test setup



O₂ impurities gas analyzer precision ±100 ppb

O2 impurities measured in the gas were less than 0.1ppm.



The pressure in the LAr was very stable at 1.05 bar.

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1 FROM "CONSTRUCTION TO OPERATION"

High-Voltage

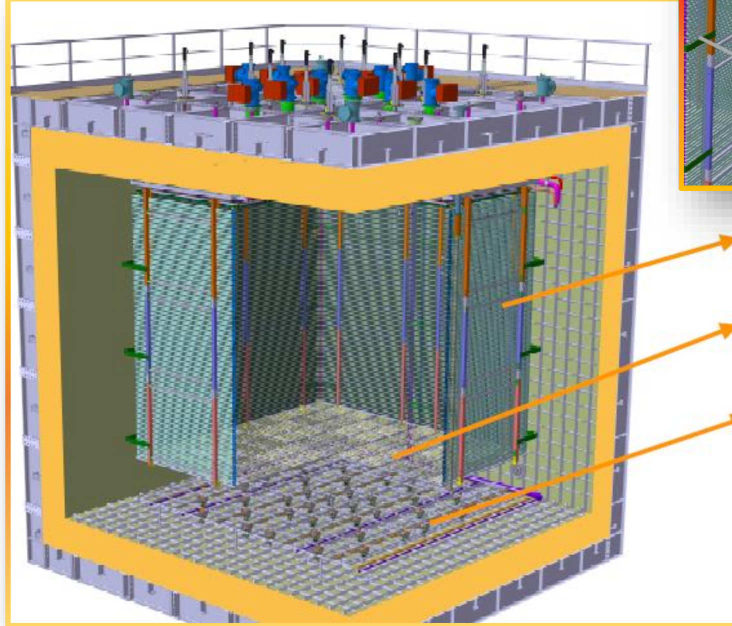
High voltage feedthrough and electrostatic simulations for protoDune-DP

C. Cantini, P. Chiu, A. Gendotti, L. Molina Bueno, S.Murphy, A. Rubbia, C. Regenfus, F. Sergiampietri, S.Wu

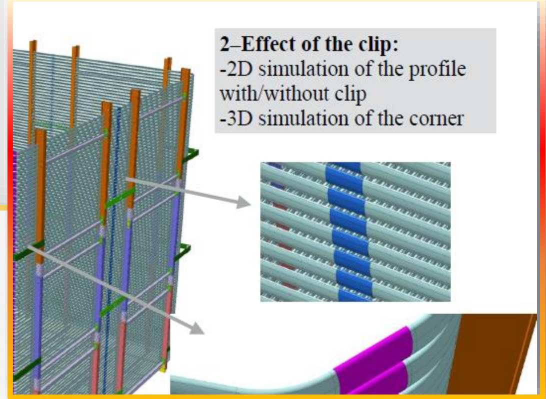
DUNE collaboration meeting, 23th-27th January 2017

The shape of the field cage and the cathode should be designed to avoid critical field regions (maximal electric field above 40 kV/cm)

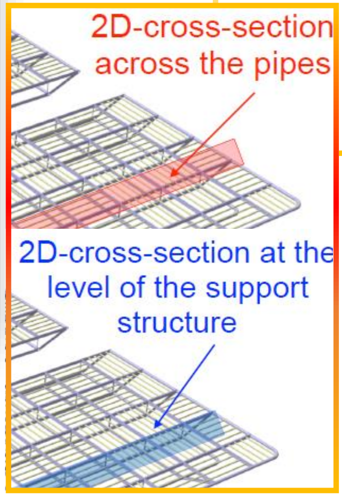
3-ELECTROSTATIC SIMULATIONS



A) Field Cage



B) Cathode



2. **Simulations:** electrostatic simulation of the whole field cage design

A. **Field cage:** final design 2D simulation performed:
- **Clip:** based on simulations, the proposed design does not represent any problem.

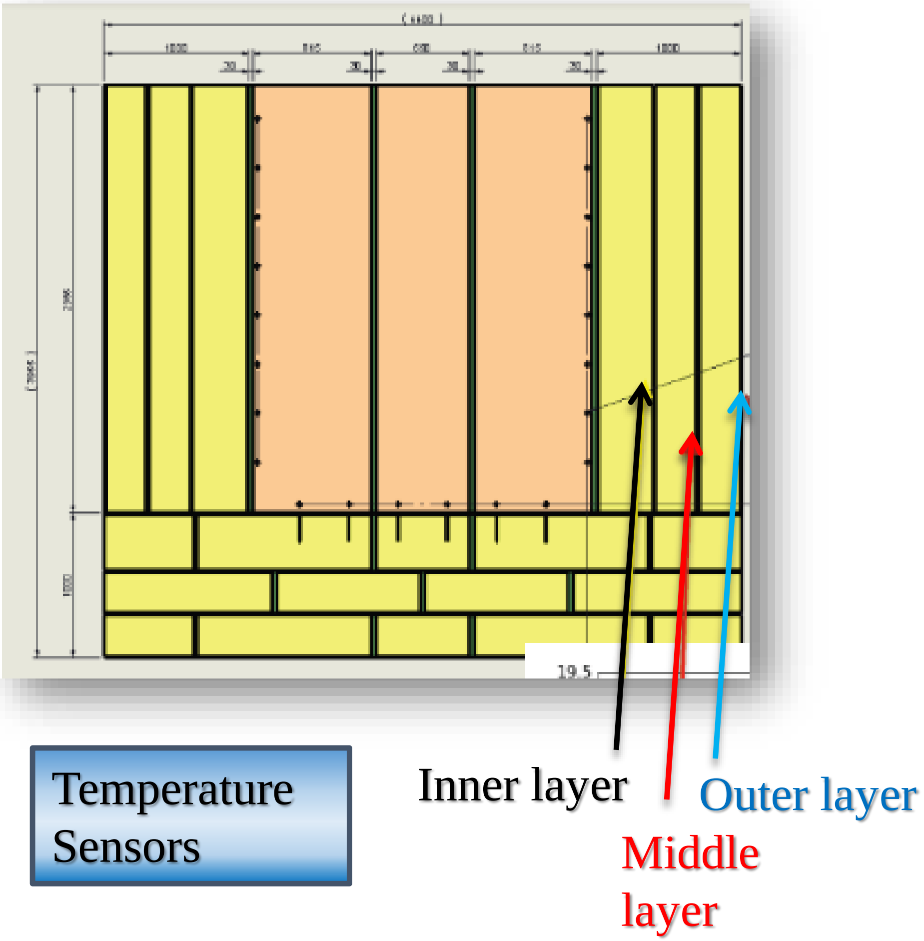
B. **Cathode:**
- Along all the structure the field is below 30 kV/cm.
- Drift field uniformity acceptable above 7 cm from the cathode.
- 3D simulations are work in progress.

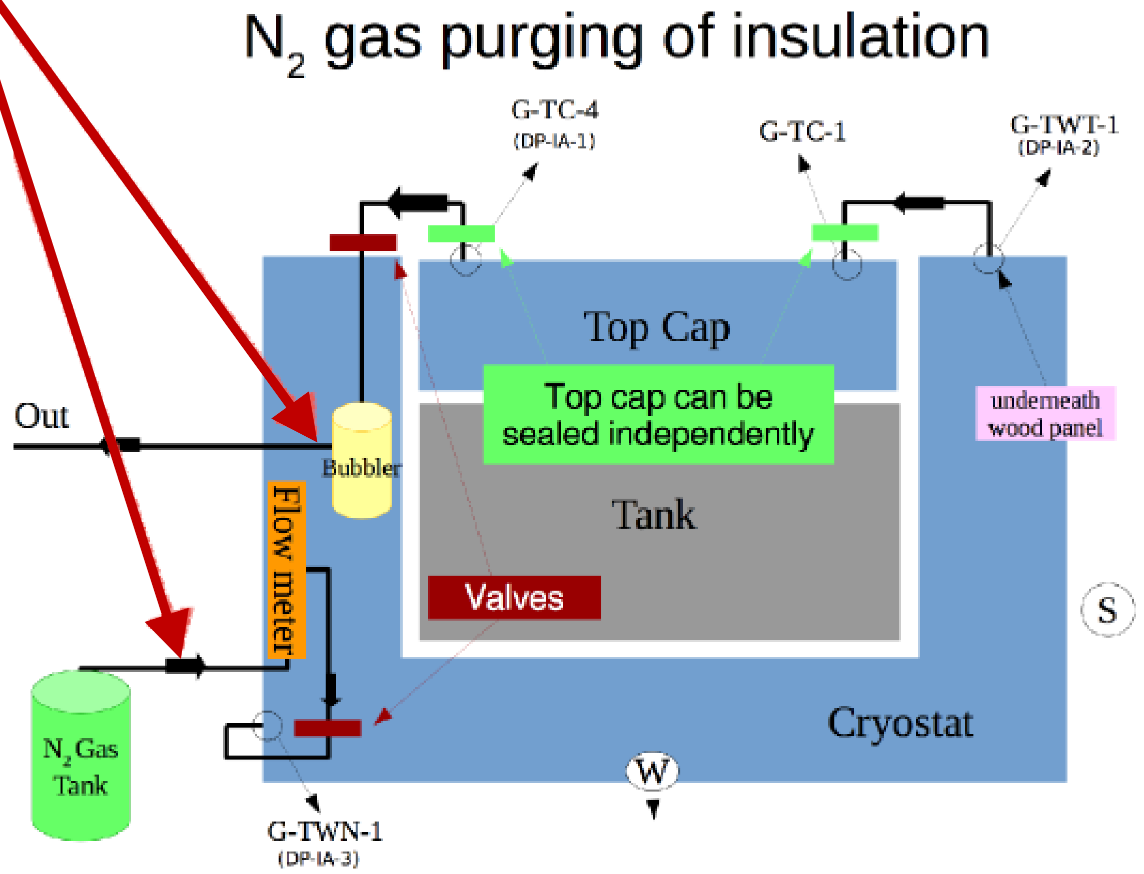
C. **Ground grid:**
- 2 mm radius wires to have a field below 30 kV/cm.

D. **High voltage feedthrough:**
- Simulation of the field along the HVFT calculated and the highest field is reached at the end of the outer conductor.
- Simulation and design of the connection between the HVFT and the cathode are work in progress.

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1
The membrane cryostat + Insulation

Gas Nitrogen Flushing of Insulation Space: the insulation space is continuously flushed with gas Nitrogen. A bubbler at the output maintains constant overpressure inside the insulation

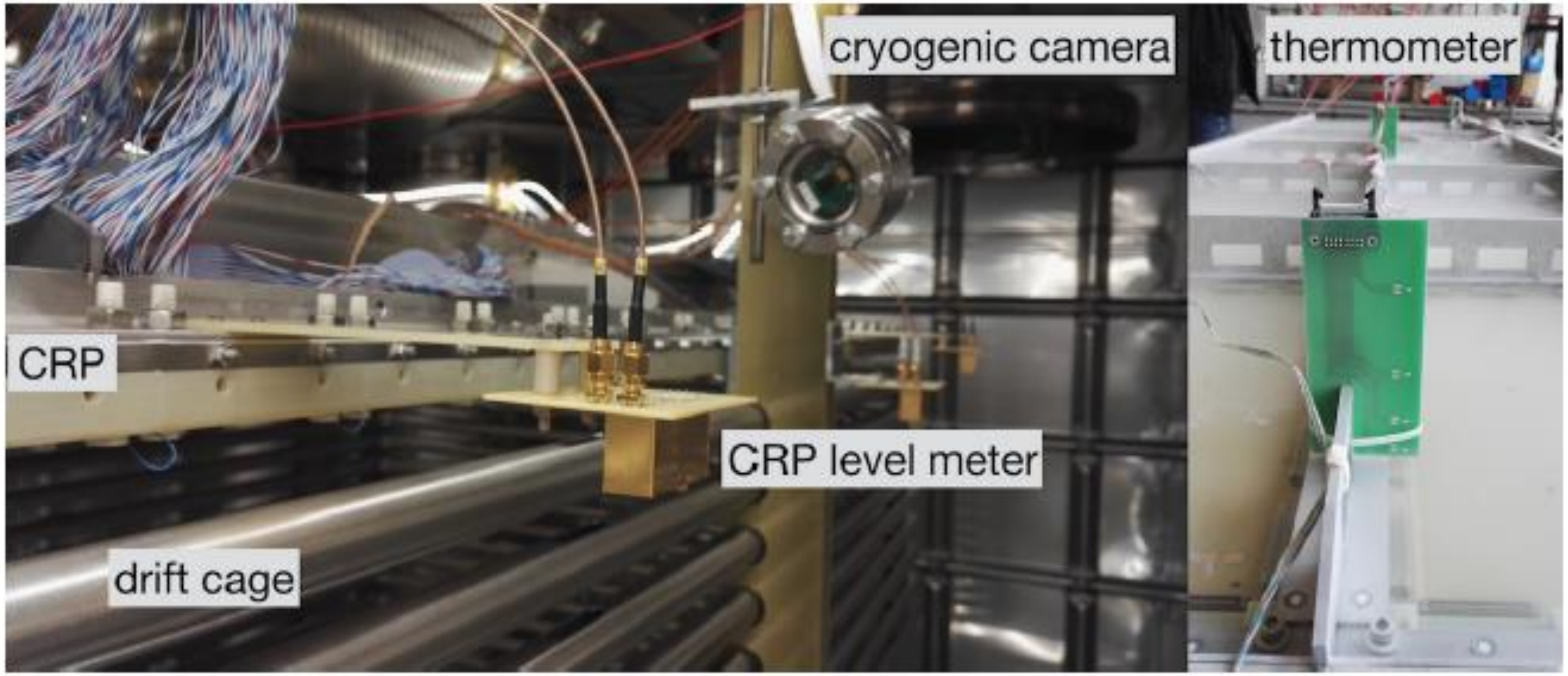




Slow Control

Provides precise monitoring of:

- -Temperatures → special thermometers to measure T gradient in gas phase
- -Pressures
- -High Voltages
- -Liquid Argon level → construction of very precise level meters



- A motorized suspension system capable of adjusting then CRP with sub-mm precision
- Custom-made cryo-cameras to provide direct view during operations and monitor the level and stability of the liquid Argon

THE DUAL-PHASE "proto" protoDUNE – The 3x1x1

Grounding